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# Spiral Grain and Annual Ring Width in Natural Unthinned Stands of Lodgepole Pine in North America

Peter Koch
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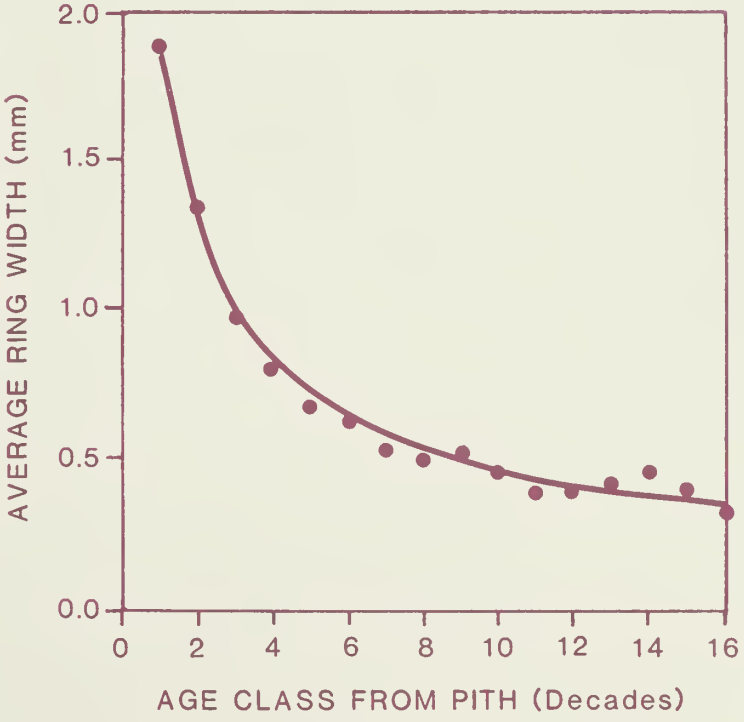

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During preparation of this manuscript, comments and a review by Dr. J. M. Harris of Christchurch, New Zealand, were particularly helpful.

## RESEARCH SUMMARY

In lodgepole pines 76 mm, 152 mm, and 228 mm in d.b.h. collected in low, medium, and high elevational zones from 37.5 to 60 degrees latitude in western North America, it was found that tree-average grain spirality tended to be greater in extreme north and south latitudes than in mid-latitudes, but did not differ with elevational zone. Volume-weighted tree-average spiral grain in variety *latifolia* ranged from 1.5 to 10.7 degrees and averaged 3.61 degrees for trees 76 mm, 4.14 degrees for trees 152 mm, and 4.79 degrees for trees 228 mm. Variety *murrayana* did not vary significantly from *latifolia* in tree-average volume-weighted spirality.

Grain spirality in stems was greatest near stump-top level. In the 2,790 stem sections examined (from all heights in trees), average grain spirality in annual rings was linearly related to age from pith, changing from about 2 degrees of left-hand spirality near the pith to about 2 degrees of right-hand spirality by the 11th (*murrayana*) to 14th (*latifolia*) decade of age from pith.

Considering all stem sections examined from stump height to 90 percent of tree height, annual ring width diminished from about 2 mm near the pith to asymptotically approach 0.3 mm in *latifolia* and 0.5 mm in *murrayana* in outermost layers of stemwood sections 10 or more decades in age.

## RELATED PUBLICATIONS

Readers interested in further studying characteristics of lodgepole pine in North America related to its utilization should find useful the following books and papers tabulated by date of publication—each part of a series on the subject:

| Citation | Subject |
|---|---|
| Koch and Burke (1985) | Exploratory study of joists made with pith-centered lodgepole pine |
| Koch (1987) | Gross characteristics of lodgepole pine in North America |
| Koch and Barger (1988) | Atlas of 28 selected commercial forest areas in the United States with unutilized stands of lodgepole pine |
| Koch and others (1989) | Proposed wood products plant to utilize sub-sawlog-size and dead lodgepole pine in northwestern Montana—a technical and economic feasibility analysis. (Particularly see chapter 4 and appendix III of this publication for characterization information.) |
| Kim and others (1989) | Chemical variation in lodgepole pine with latitude, elevation, and diameter class |
| Pellerin and others (1989a) | Mechanical properties of lodgepole pine: 3-inch diameter stems |
| Kossuth and Koch (1989) | Extractives content of lower stemwood and taproot |
| Pellerin and others (1989b) | Mechanical properties of lodgepole pine: 6- and 9-inch diameter stems |
| Campbell and others (1990) | Chemical variation in lodgepole pine with sapwood/heartwood, stem height, and variety (includes ultimate and proximate analyses) |
| Wiedenbeck and others (1990) | Air permeability, shrinkage, and moisture sorption of lodgepole pine stemwood |
| Koch and others (1990) | Incidence of compression wood and stem eccentricity in lodgepole pine stemwood |
| Burke and others (in preparation) | Anatomical variations of lodgepole pine in North America |

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## SPIRAL GRAIN AND ITS IMPLICATIONS IN WOOD PRODUCTS

Lodgepole pine products are said to be **cross grained** wherever the wood tracheids are not aligned parallel to product longitudinal axis. Cross grain can be caused by grain distortions around knots, by sawing crooked logs, and by sawing, edging, or ripping boards so that saw lines are not parallel to tracheid alignment. Logs having crook or pronounced taper, if rotary-cut, will produce cross-grained veneer.

A serious and perhaps more prevalent cause of cross grain in lodgepole pine is **spiral grain** in the standing tree (figs. 1 and 2). The angle of spiral varies among and within trees. Extensive data have not been published broadly elucidating the incidence of spiral grain in lodgepole pine over its principal range, but it is a major defect of the species in some localities.

Spiral grain causes twisting distortion of roundwood products as the products dry below fiber saturation (visualize the problems caused by posterection twisting of power poles carrying crossarms). Also, sawn products such as studs warp on drying if they contain significant spiral grain—thereby diminishing their usefulness.

Additionally, the cross grain in sawn products caused by presence of spiral grain significantly reduces important mechanical properties of the wood. The reduction is related to the **slope of grain** in wood—that is, the ratio between a 1-cm deviation in the grain from the edge or long axis of the piece and the distance in centimeters for which this deviation occurs. For example, wood with a slope of grain of 1 cm in 5 cm (an angle of 11.3°) can be expected to have only 55 percent of the modulus of rupture of a straight-grained piece, 36 percent of the impact bending strength, and 93 percent of the crushing strength parallel to the grain (USDA FS 1974, pp. 4-27).

Woodworkers manufacturing split-wood products know that extreme spiral grain, or reversals in direction of spiral grain from pith to bark, make the work of splitting more difficult—and the split-wood products less valuable. As will be further discussed in the Results section, logs with straight grain or only a small left-hand spiral showing at log surface

**Figure 1**—Right-hand spiral grain in stems of air-dried, pole-size lodgepole pine in the Meadows area of the Okanogan National Forest.

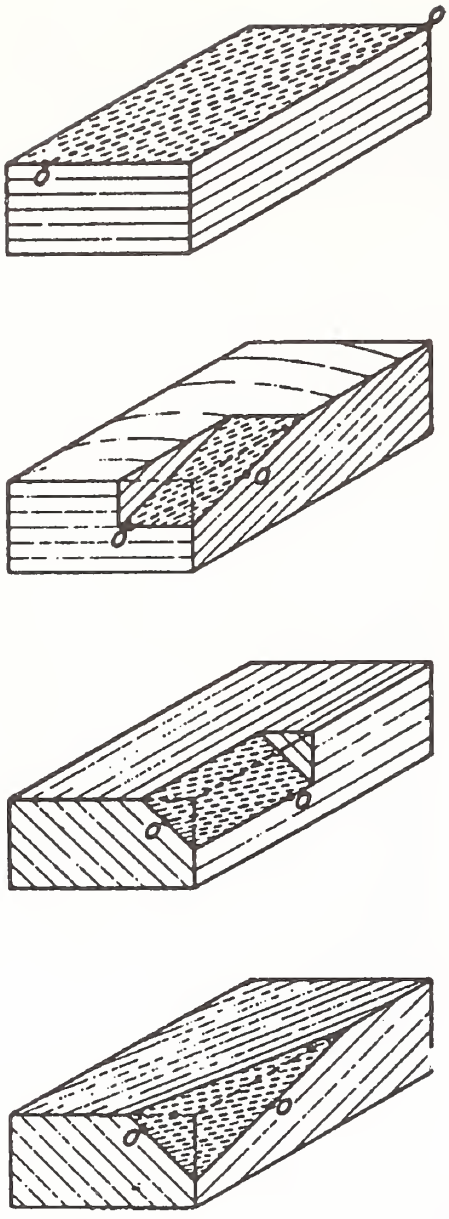


**Figure 2**—Schematic views of wood specimens containing spiral grain illustrate the relationship of tracheid orientation (0-0) to the axes of the pieces. (Drawing after U.S. Department of Agriculture, Forest Service 1974, pp. 4-29.)

are less likely to have spiral grain reversal than those that show a right-hand spiral under the bark.

Also, extreme spiral grain in roundwood products (fig. 1) makes them less desirable for uses where resulting spiral checks detract from the appearance of the finished products—for example house logs. In utility poles, spiral grain accelerates decay because spirally oriented checks (fig. 1) hold moisture longer than checks in straight-grained poles.

In summary, spiral grain causes unsightly drying checks in roundwood products, drying distortions in both roundwood and sawn products, diminution of most important mechanical properties in roundwood and sawn products, and acceleration of decay in utility poles.

The problem faced by North American manufacturers of lodgepole pine products is that the literature affords no assessment (locally or range-wide) of the severity of spiral grain in the stemwood of the species, and hence manufacturers have no rationale for avoiding stems or stem portions with excessive spiral grain; neither do they have a clear picture of its pervasiveness.

## STUDY SCOPE AND OBJECTIVES

The purpose of this study was to ascertain the incidence and degree of spiral grain in the stemwood of the two principal varieties of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. and *Pinus contorta* var. *murrayana* [Grev. and Balf.] Engelm.) throughout their major ranges in North America (fig. 3), and to correlate this incidence with distance and age from pith, pith eccentricity, and stem out-of-roundness (and with other selected characteristics such as latitude, longitude, elevational zone, diameter at breast height, tree height, height in tree, magnitude of stem crook, compression wood content, stemwood specific gravity, average growth-ring width at stump height, growth-ring width at sample point, stemwood fiber length at each height in stem, crown ratio, live-crown length, number of branches, average branch diameter, stem taper, length of taproot, and proportions of complete-tree weight represented by roots, bark, stemwood, branchwood, and foliage). Additionally, within-tree radial patterns of spirality were noted.

Incidental to the study were observations on width of growth rings, height growth, and annual volume and weight growth increments of stemwood in *latifolia* and *murrayana*.

The primary objective during tree collection was to obtain disease-free and insect-free specimens of 76-, 152-, and 228-mm (3-, 6-, and 9-inch) lodgepole pine (var. *latifolia*) at low, medium, and high elevations from nine equally spaced north latitudinal zones (40 to 60 degrees) across 10 degrees of longitude, in such a way as to encompass the major range of this variety (fig. 3).

A secondary objective was to sample these same three diameter classes of var. *murrayana* at mid-elevation at four north latitudes (37½, 40, 42½, and 45 degrees) in California and southern Oregon at a single longitude per latitude (fig. 3).

The trees of both varieties were sampled in such a way that between-variety comparisons could be

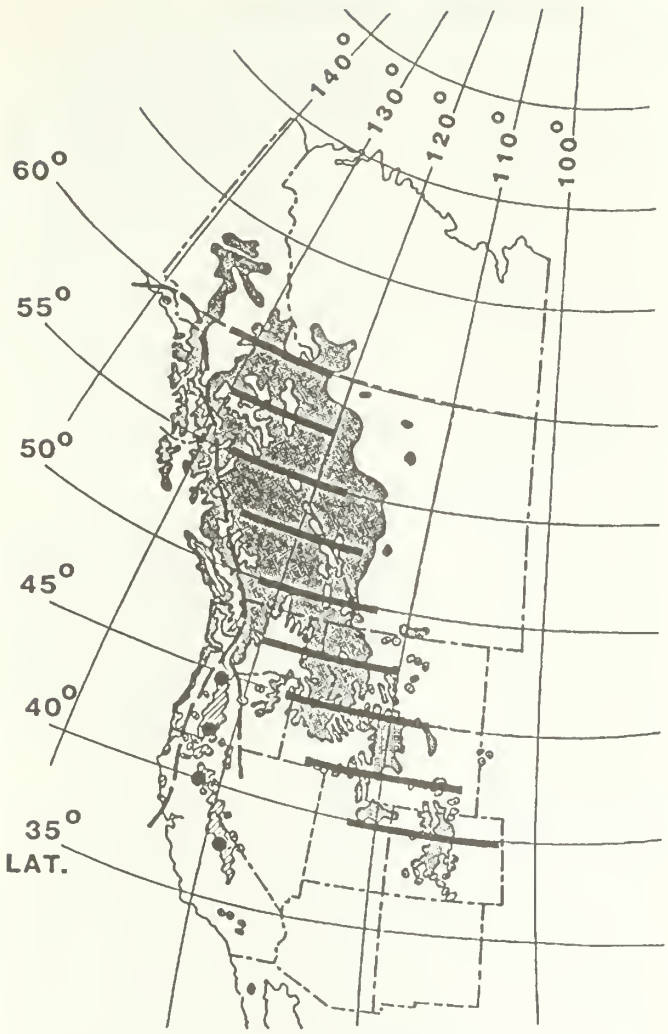



**Figure 3**—Sampling zones superimposed on Little's (1971) range map of lodgepole pine in North America. Variety *latifolia* is mapped to the right of the dashed lines, *murrayana* between them, and *contorta* to the left of them. Variety *contorta* was not studied because of its small potential for commercial use.

made for midelevation trees from latitudes 40, 42½, and 45 degrees. The collection totaled 243 *latifolia* trees and 36 *murrayana* trees.

See table 1 for summary information on these 279 trees.

## LIMITATIONS OF THE STUDY

A work of this scope, describing trees of a species with great latitudinal, longitudinal, and elevational range, cannot meet the needs of readers of all disciplines. Recognizing this reality, the work was written principally for use by industrialists, scientists, process engineers, and students who need a description of gross species characteristics and some appreciation of their variations within North America.

Because the sampling plan calls for a specimen collection stratified by d.b.h., latitude, and elevational zone—without sampling intensity adjusted for volume distribution within these stratifications—it does not permit computation of species-average values valid range-wide.

Moreover, the sampling plan does not permit evaluation of effects of site quality, age, and stand density—even though it is well known that these three parameters significantly affect many, perhaps most, of the characteristics evaluated. This shortcoming in experimental design was thoroughly discussed before study initiation.

As resources available for this study of lodgepole pine as an industrial raw material were not only finite, but also modest, the study objectives were limited to determination of broad material-characteristics variations related to tree d.b.h. and spatial location (latitude, longitude, and elevational zone). The study was not designed to deal with the very complex relationships involving site quality, tree age, or stand density; as a result, the sampling plan does not permit such analyses.

The elevational range of lodgepole pine (*latifolia*) is considerably greater in southern latitudes than in northern (fig. 4); and it is probable that site quality and stand densities vary less in northern than in southern latitudes.

## THE LODGEPOLE PINE RESOURCE IN NORTH AMERICA

To appreciate the scope of the work and to understand the rationale for the sampling design, it is useful to know something about the resource.

Lodgepole pine (*Pinus contorta* Dougl. ex Loud.) occupies about 5¼ million ha of commercial forest land in the United States (containing 748 million $m^3$ of lodgepole growing stock and over 71 billion board feet of lodgepole timber, mostly in Montana, Idaho, Wyoming, Colorado, and Oregon), and is the fourth most extensive timber type west of the Mississippi River. On these 5¼ million ha, a significant proportion of the trees are dead, having been killed by insects and disease. In the Northern Region alone, a 1979 survey reported 540,862 ha severely infested with mountain pine beetle. The most recent survey data for Idaho indicate that insects and disease have killed about 1 percent of the lodgepole pine trees. Canada has a greater acreage of lodgepole pine forest type (20 million ha) than the United States, comprising 22 percent of the total forest land in western Canada.

Table 1—Summary information descriptive of the 279 lodgepole pines in the study. Data averaged over full range of sample, by variety

| Variable | Tree d.b.h. 76 mm | 152 mm | 228 mm |
|---|---|---|---|
| ***Latifolia* (81 trees of each diameter)** | | | |
| Age at 152-mm-high stump top, years | 73 | 92 | 104 |
| Height from 152-mm-high stump top to apical tip, meters | 9.3 | 15.6 | 19.1 |
| Taproot length measured from 152-mm-high stump top, centimeters | 55 | 78 | 94 |
| Average width of annual rings at 152-mm-high stump top, millimeters | .7 | 1.0 | 1.3 |
| Average diameter outside bark of live branches 50-mm from stem, millimeters | 9 | 13 | 19 |
| Average branch angle, degrees[1] | 85 | 79 | 77 |
| Ratio of live-crown length to tree height (crown ratio) | .48 | .44 | .45 |
| Number of live branches | 64 | 108 | 133 |
| Number of dead branches | 57 | 100 | 119 |
| Stem taper inside bark below live crown, millimeters per meter | 6.3 | 7.8 | 10.5 |
| Stem taper inside bark from base of live crown to apical tip, millimeters per meter | 13.1 | 15.9 | 18.5 |
| Stemwood-average moisture content, percent | 99 | 100 | 98 |
| Stemwood-average specific gravity[2] | .43 | .42 | .41 |
| ***Murrayana* (12 trees of each diameter)** | | | |
| Age at 152-mm-high stump top, years | 63 | 82 | 86 |
| Height from 152-mm-high stump top to apical tip, meters | 7.4 | 13.7 | 18.7 |
| Taproot length measured from 152-mm-high stump top, centimeters | 58 | 91 | 97 |
| Average width of annual rings at 152-mm-high stump top, millimeters | .7 | 1.1 | 1.6 |
| Average diameter outside bark of live branches 50-mm from stem, millimeters | 7 | 12 | 18 |
| Average branch angle, degrees[1] | 88 | 83 | 78 |
| Ratio of live-crown length to tree height (crown ratio) | .60 | .55 | .59 |
| Number of live branches | 72 | 127 | 146 |
| Number of dead branches | 34 | 79 | 94 |
| Stem taper inside bark below live crown, millimeters per meter | 5.8 | 10.8 | 11.9 |
| Stem taper inside bark from base of live crown to apical tip, millimeters per meter | 14.5 | 16.0 | 16.6 |
| Stemwood-average moisture content, percent | 98 | 114 | 121 |
| Stemwood-average specific gravity[2] | .48 | .44 | .41 |

[1]Angle between branch and stem; upward-pointing branches less than 90°; drooping branches more than 90°.
[2]Based on green volume and ovendry weight.

Most of the North American lodgepole pine resource is of the variety *latifolia* (*Pinus contorta* var. *latifolia* Engelm.) centered along the Rocky Mountains from 40 to 60 degrees north latitude, with Sierra lodgepole pine (*Pinus contorta* var. *murrayana* [Grev. & Balf.] Engelm.), and shore pine (*Pinus contorta* Dougl. ex Loud. var. *contorta*) comprising significantly lesser volumes on Sierra and coastal areas (fig. 3). A fourth variety, (*bolanderi* [Parl.] Vasey), is a shrub local in Mendecino County, CA.

In both Canada and the United States, much of the lodgepole resource is in older (60-200 years), virtually stagnated stands in which growth rate is very low and mortality very high. Typically trees are

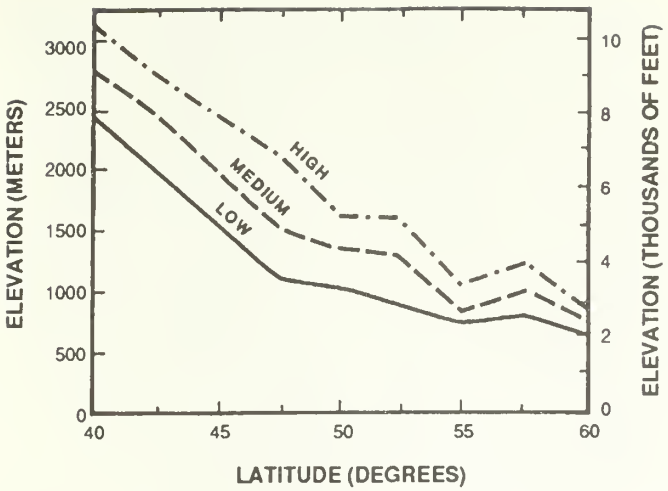



**Figure 4**—Elevational trends in the three zones (low, medium, and high) where lodgepole pine (var. *latifolia*) was sampled along nine latitudes. Each plotted point is the average for nine trees; that is, three diameters by three replications.

small in diameter. Slightly more than one-third of the volume (ovendry weight basis) is in trees less than 175 mm in diameter measured at breast height outside bark (Van Hooser and Chojnacky 1983); such a diameter might be considered the lower limit for lumber manufacture.

Silvicultural treatments (thinning or removal and regeneration to a managed stand with controlled stocking) are so expensive, and stumpage revenue so little, that much of the acreage has received no treatment to accelerate growth and slow mortality. As timber shortages further develop in the Rocky Mountain Region during the 21st century, more intensive silvicultural treatment of lodgepole pine may become advantageous.

## PAST AND CURRENT WORK

Spiral grain has been reported in nearly 200 species of hardwoods and softwoods (Wellner and Lowery 1967). Summaries of this literature have been prepared by Noskowiak (1959), Nicholls (1963), Northcott (1965), and Bannon (1966). More recently published, Harris's (1989) text on spiral grain is an up-to-date and thorough review of world literature on the subject; his review covers both hardwoods and softwoods.

While the literature affords considerable data on spiral grain in many species of conifers, information specific to spiral grain in lodgepole pine is not abundant. Papers providing such information are summarized in the following text under the headings of Genetics, Physiology, Prevalence and Patterns of Spirality, Environmental Conditions Related to Spiral Grain, and Effects on Products—all accompanied by some general conclusions of Harris (1989).

### Genetics

Although no data specific to genetic control of spiral grain in lodgepole pine are extant, within the world body of literature on spiral grain there is some evidence that spiral grain is a heritable characteristic (Champion 1925, 1927, 1930).

Harris (1989) introduces his discussion of genetics as follows:

> That spiral grain, together with interlocked and wavy grain, are under a considerable degree of genetic control is self evident. Some species, such as *Pinus roxburghii* are notorious for developing spiral grain, whereas others like *Fagus sylvatica* are usually straight-grained. Similarly, whole genera such as *Entandrophragma* and *Eucalyptus* contain many species in which interlocked grain is normal, whereas it is completely absent from other genera. Even wavy grain, though apparently not inevitable in any individual tree, is regularly encountered in some species, whereas there are others in which its presence has never been recorded.

In his conclusions regarding genetics, Harris (1989) observes that "the existence in many species of marked differences in grain spirality between geographical origins indicates the potential for screening provenances as well as phenotypic selection of plus trees." He also notes, however, that there appear to be some species in which genetic control of spirality is negligible.

### Physiology

In radial files of lodgepole pine (var. *latifolia*) tracheids having changing orientations, Savidge and Farrar (1984) traced through serial tangential sections to deduce events in fusiform cambial cells associated with spiral grain formation. They concluded that a primary event contributing to orientation changes in such fusiform cambial cells is repetitive, homogeneously sloping, pseudo-transverse, anticlinal divisions in these cells. Imperfect periclinal divisions in these cells also contribute to spiral grain formation.

As will be discussed in the Results section of this paper, virtually all lodgepole pine stems display a left-hand spiral within the first few annual rings from the pith. This phenomenon is common to most conifers.

Harris (1989) believes from observations of *Pinus radiata* that the needle traces (vascular connections to the short shoots) are the causative agents, acting

as interruptions directing auxin flow (fig. 5). He notes:

> This possibility is difficult to demonstrate mathematically, but was illustrated by recording the passage of steel balls running down an inclined plane into which nails had been inserted in the pattern of stem parastichies. The distribution of the steel balls after they had traversed this "bagatelle board" was strongly skewed in the direction of the steeper of the primary "spirals." ...Although there are obvious limitations to the application of these results to conditions in a tree, they did indicate that the distribution of needle traces around the stem could favor generation of spirality in the flow of auxin, as long as it moves under conditions approaching free flow.

**Figure 5**—Portion of stem of *Pinus radiata* into which wooden pegs were driven to supplement the original needle traces after the stem needles had been shed. Grain angle in the previous year's growth (here revealed by turnery) is maintained in the area so treated, but decreases in the untreated stem below. (From Harris 1969.)

Harris (1989) further concludes that "fusiform initials may react directly to auxin vectors (changing their orientation by angles less than 1° between periclinal divisions), in addition to the readily recognizable processes of uniformly oriented pseudo-transverse divisions followed by intrusive growth."

In lodgepole pine, and many other conifers, the left-hand spirality will frequently attain a maximum within a few annual rings of the pith and then, with additional years from the pith, slowly pass through zero spirality to right-hand spirality (fig. 1) in later years. It is this reversal—usually occurring only once during the life of a lodgepole pine tree—that is difficult to explain. In addressing this question, Harris (1989, p. 130) concludes in part:

> 1. The arrangement and orientation of cambial cells very largely predetermines the relative position and arrangement of the various xylem derivatives, and hence the grain angles of wood.
> 2. Several types of oriented morphogenetic events occur in the cambium. Four types of events that have been shown to leave behind a clear record in the xylem can be used to study the origins of changing grain angles. The events are of two forms [fig. 6]: those that tend to change existing orientation toward the right (Z events), and those that induce changes to the left (S events).
> 3. The orientation of morphogenetic events within the cambium is generally non-random. At any one time considerable areas of cambium, called cambial domains, can be shown to contain morphogenetic events almost exclusively of the S or Z type.
> 4. Within particular areas of cambium, reversals of the predominating direction occur with time. This can be interpreted as migration of domain boundaries along the stem.

## Prevalence and Patterns of Spirality

The prevalence of spiral grain in var. *murrayana* of lodgepole pine early caught the attention of researchers. In the 1880's Bradley (1918) noted two locations in which stands of insect-killed trees had shed their bark—permitting easy perception of occurrence of spiral grain; at one location he tallied 250 trees with spiral grain in which 80 percent showed right-hand spiral. In another location a similar tally showed about 70 percent with left-hand spiral. (Right-hand spiral twists upward to the right and left-hand spiral twists upward to the left, as viewed by a person facing the tree stem; thus the stems in figure 1 all show right-hand spiral.)

From observation of var. *murrayana* in California's high Sierra country near Mount Whitney and above the Kern River Canyon, Gunther (1929) concluded that young lodgepole pine in these latitudes do not develop spiral grain until their topmost leaders extend several feet above the surrounding canopy.

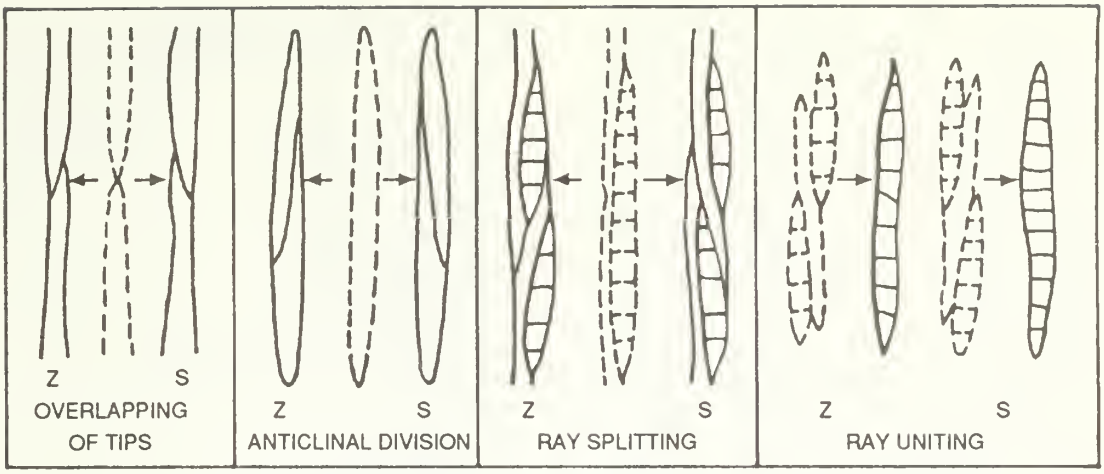



**Figure 6**—Four types of morphogenetic events in cambial cells giving rise to RH (Z) or LH (S) grain angles. (From Hejnowicz 1973.)

Gunther observed that such exposed leaders became deformed (or died) and that such leader deformation or death is accompanied by development of spiral grain—first in upper stem portions and later in the lower stem.

Lodgepole pine has been introduced—and planted extensively—in Scandinavian countries and in England, Scotland, and the Republic of Ireland. Although there is a large body of literature related to performance of the species in these countries, only two observations on the prevalence of spiral grain were found. Thomas (1966), in studies of lodgepole pine plantations in England, Scotland, and the Republic of Ireland established from coastal Washington seed, found that "grain was usually straight and the incidence of inclined grain was generally low; even in early growth the angle of inclination was quite slight." The trees he studied were 28 to 43 years old and measured 10 to 12 inches in diameter at breast height (d.b.h.), and 50 to 60 feet in height.

Brazier (1980) reported that in lodgepole pine grown at Blessington, Eire, spiral grain was not a significant defect. In another study in North Wales, Brazier again found the average grain inclination in stemwood of lodgepole pine was low. While some differences between seed sources (British Columbia, Idaho, and Washington) were observed, Brazier concluded that "all the evidence points to spiral grain being of minor importance in lodgepole pine and unlikely to be of significance in affecting choice of provenance."

In a study of twist in 16 utility poles specially selected in Montana from lodgepole pine with spiral grain, Lowery and Erickson (1967) found that moderate severity of spiral grain in pole exteriors yielded a slope of grain of 1 inch in a length of more than 16 inches. Poles with severe spiral grain had a slope of grain of 1 inch in 16 inches or less. Because the poles were specially selected, however, the experiment did not provide data on average severity of spiral grain in the species.

Wellner and Lowery (1967) reported on a study of 800 utility poles from pole yards in Spokane and Newport, WA, and Priest River and Sandpoint, ID. The poles were of several coniferous species, including lodgepole pine. They found that only 1 percent had a slope of grain of 1:10 or more severe; 6½ percent of the poles had a slope of grain between 1:11 and 1:20; and 48 percent of the poles were practically straight-grained (1:201 or more), as follows:

| Slope of grain | | Percent of poles |
|---|---|---|
| *Slope* | *Degrees* | |
| 1:1-10 | >5.7 | 1.0 |
| 1:11-20 | 5.2-2.9 | 6.5 |
| 1:21-50 | 2.7-1.2 | 19.0 |
| 1:51-100 | 1.1-0.6 | 14.0 |
| 1:101-150 | 0.6-0.4 | 7.5 |
| 1:151-200 | 0.4-0.3 | 4.0 |
| 1:201+ | <0.3 | 48.0 |
| | | 100.0 |

Wellner and Lowery further observed that 66 percent of these poles had left-hand spirality and only 34 percent showed right-hand spirality on exterior surfaces. Forty-four percent of the poles exhibited maximum grain inclination in the top section of the pole; percentages of the poles exhibiting maximum grain inclination in the middle and butt sections were 26 and 30 percent, respectively.

In a study of western larch (*Larix occidentalis* Nutt.) from northern Idaho and northwestern Montana, Wellner and Lowery (1967) found a strong relationship between crown length and the ratio of trees having left-hand spiral to trees having

right-hand spiral (fig. 7); they concluded that trees in open stands—that is, trees with long crowns and rapid growth rate—tend to have grain that spirals to the left, and that trees in very dense stands (that is with short crowns and slow diameter growth) tend to have grain that spirals to the right. All of these observations were made at stem surface only.

Lowery (1966) provided a spiral-grain classification system and data specific to lodgepole pine butt logs from St. Anthony, ID (fig. 8). As spirality changes in degree (and frequently in direction) with radial position in the stem, his pattern classification system diagrams the initial spiral direction near the pith, change in magnitude of the grain slope from pith to periphery, and changes in direction of slope.

Lowery (1966) found that for these butt logs of lodgepole pine sampled at St. Anthony, ID, pattern number 5 was predominant, that is, right spirality increasing with distance from the pith. Initial spiral direction near the pith in these lodgepole pine logs was 30 percent left and 69 percent right. One out of the 113 logs sampled was classified as straight-grained (pattern 9 in fig. 8). In related work with other coniferous species, he found no evidence of geographic variation in spirality patterns.

Koch and Barger (1988) sampled a pair of lodgepole pines 3.5 to 4 inches in d.b.h. from each of 28 public forests in six northwestern States, and took specimens of stemwood at 20 percent of tree height. Spiral grain at the outer surface of these specimens of small stemwood—when airdry—averaged 1.9 degrees with standard deviation of 1.98 degrees and range from 0 to 8 degrees, as follows:

| State and Forest | Spiral grain at surface | |
|---|---|---|
| | Tree #1 | Tree #2 |
| | *Degrees* | |
| Colorado | | |
| Gunnison NF | 5 | 5 |
| Rio Grande NF | 7 | 3 |
| White River NF | 0 | 8 |
| State Forest | 7 | 3 |
| Bureau of Land Management | 2 | 1 |
| Idaho | | |
| Caribou NF | 0 | 1 |
| Challis NF | 1 | 2 |
| Nez Perce NF | 2 | 3 |
| Idaho Panhandle NF | 0 | 1 |
| Payette NF | 3 | 2 |
| Salmon NF | 0 | 0 |
| Montana | | |
| Deerlodge NF | 0 | 1 |
| Flathead NF | 2 | 1 |
| Gallatin NF | 2 | 2 |
| Helena NF | 0 | 1 |
| Kootenai NF | 0 | 0 |
| Oregon | | |
| Fremont NF | 2 | 1 |
| Malheur NF | 1 | 3 |
| Mt. Hood NF | 1 | 3 |
| Utah | | |
| Ashley NF | 1 | 3 |
| Washington | | |
| Colville NF | 0 | 0 |
| Okanogan NF | 5 | 2 |
| Wenatchee NF | 2 | 5 |
| State Forest | 3 | 0 |
| Wyoming | | |
| Bighorn NF | 0 | 1 |
| Bridger-Teton NF | 0 | 0 |
| Medicine Bow NF | 0 | 4 |
| Shoshone NF | 1 | 4 |

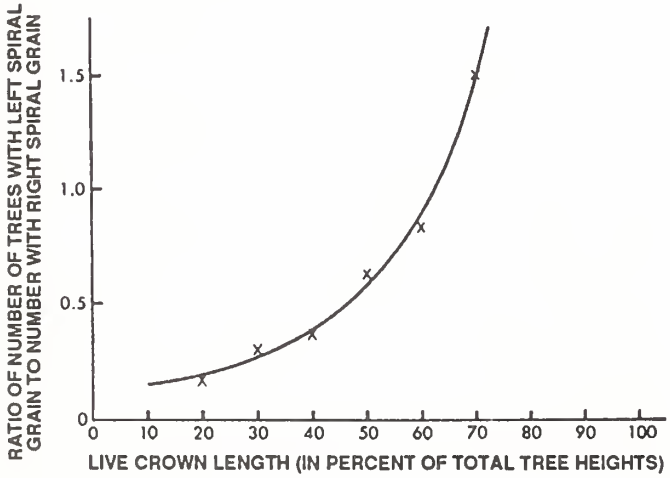


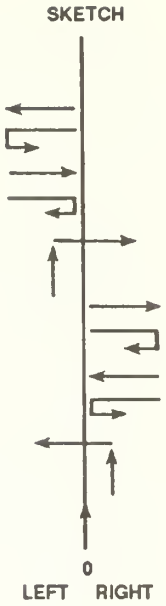

Figure 7—Relation of live crown length in western larch to ratio of trees having left-hand spiral grain to trees having right-hand spiral grain at stem surface. Only trees with spiral-grain ratio of 1:50 or more severe were included in the plot. (Drawing after Wellner and Lowery 1967.)

Burke and Koch (1987) sampled 16.5-foot stem lengths from 151 small lodgepole pine trees selected from stagnated stands in northwestern Montana. More specifically, the stands were located in the Miller Creek drainage of the Kootenai National Forest 20 miles southeast of Libby, MT, near Olney, MT, in the Flathead National Forest, and from private lands near Coram, MT. Butt minor diameters of the bark-free 16.5-foot long sections ranged from 3.0 to 4.8 inches.

While green, half were turned (pith-centered) into dowels measuring 2.25 inches in diameter and the other half into dowels 2.50 inches in diameter.

A

| SPIRIAL GRAIN PATTERN CODE | DESCRIPTION |
|---|---|
| 1 | LEFT INCREASE AWAY FROM ZERO |
| 1A | LEFT INCREASE, THEN DECREASE TOWARD ZERO |
| 2 | LEFT DECREASE TOWARD ZERO |
| 2A | LEFT DECREASE, THEN INCREASE AWAY FROM ZERO |
| 3 | CHANGE FROM LEFT TO RIGHT SPIRALITY |
| 4 | LEFT SPIRAL WITH LITTLE CHANGE |
| 5 | RIGHT INCREASE AWAY FROM ZERO |
| 5A | RIGHT INCREASE, THEN DECREASE TOWARD ZERO |
| 6 | RIGHT DECREASE TOWARD ZERO |
| 6A | RIGHT DECREASE, THEN INCREASE AWAY FROM ZERO |
| 7 | CHANGE FROM RIGHT TO LEFT SPIRAL |
| 8 | RIGHT SPIRAL WITH LITTLE CHANGE |
| 9 | ESSENTIALLY STRAIGHT GRAIN |




B

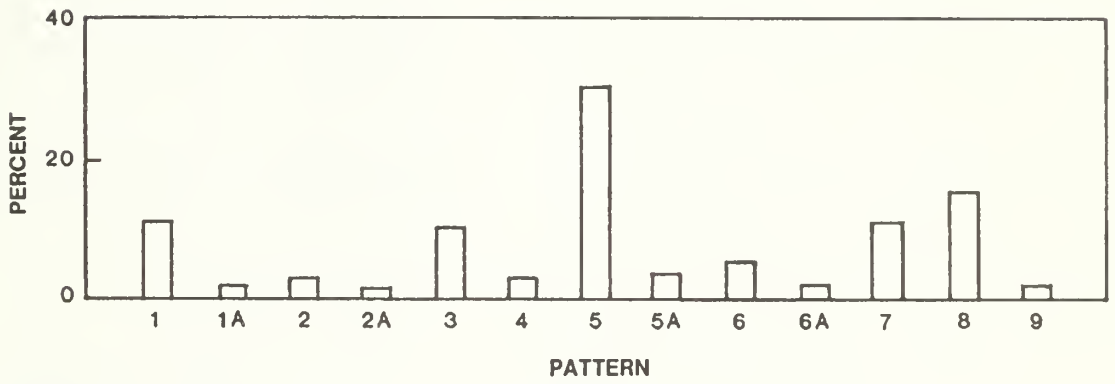



**Figure 8**—(A) Spiral grain patterns found in lodgepole pine. (B) Frequency distribution of lodgepole pine disks by spirality pattern. (Drawings after Lowery 1966.)

The dried dowels were subsequently used as flanges in fabricated joists of very high strength and stiffness.

Because the surfaces of the 2¼- and 2½-inch dowels were only 1 to 1½ inches from the pith, the wood had insufficient years to develop severe spiral grain. Spiral grain of the small magnitude noted (table 2) had insignificant correlation with modulus of elasticity of the dry dowels ($r$ = +0.170 and +0.075 for the 2¼- and 2½-inch dowels, respectively). Neither was dowel spiral grain significantly correlated with stem-section sweep.

Dowel spiral grain did, however, have weak positive correlation with dowel specific gravity based on ovendry weight and green volume ($r$ = +0.343 and +0.137 for 2¼ and 2½ inch dowels, respectively); that is, dowels of high specific gravity had a slightly greater degree of spiral grain than dowels of low specific gravity. See the Results section for further comment on this relationship.

As noted previously, a common spiral-grain pattern of conifers is one in which grain in the first annual growth ring is parallel to the pith but in immediately following rings develops a left-hand spiral that within a few years increases to a maximum left-hand spiral, then diminishes to zero, and finally becomes increasingly right-hand as the tree ages. The outermost annual ring on the exterior of a tree with such a pattern has been described by Burger (1941), Hendrickson and Vité (1960), Brazier (1965), and Harris (1989) and can be visualized as follows (fig. 9): Primary and first-formed secondary xylem at the tip of the apical shoot are straight-grained, but left-hand spiral grain develops lower down, reaching a maximum value at some years' growth below the apex.

Table 2—Some data related to lodgepole pine pith-centered dowels turned green to 2.25 and 2.50 inches in diameter from 16.5-foot-long stem sections of small lodgepole pines sampled in northwestern Montana

| Property | Mean | Standard deviation | Range |
|---|---|---|---|
| **2.25-inch dowels ($n$ = 75)** | | | |
| Sweep of 16.5-foot stem section with bark, inches | 0.9 | 0.5 | 0.3 - 2.4 |
| Dowel specific gravity (ovendry weight and green volume) | .42 | .02 | .36 - .46 |
| Spiral grain on dowel surface, degrees | 1.4 | 1.0 | 0 - 5.0 |
| **2.50-inch dowels ($n$ = 76)** | | | |
| Sweep of 16.5-foot stem section with bark, inches | .7 | .3 | .2 - 2.2 |
| Dowel specific gravity (ovendry weight and green volume) | .43 | .02 | .37 - .48 |
| Spiral grain on dowel surface, degrees | 1.5 | 1.2 | 0 - 5.0 |

Farther down the stem the grain angle will decrease to zero at some later year's growth below the apex, and from there to the base of the stem there will be increasing right-hand spiral grain. A line following grain direction down the outside of the stem from top to bottom will describe three-quarters of a complete wave form (fig. 9). From this description it is obvious that a true picture of stem spirality can be obtained only by an assay that includes variation with radius and height in stem.

Thus it is difficult to assess stem spirality from viewing the exterior of a bark-free stem—even if the stem is checked from drying. It is even more difficult (impossible?) to assess stem spirality pattern from the external appearance of a living conifer sheathed in bark.

## Environmental Conditions Related to Spiral Grain

Harris' (1989) review of spirality contains references reporting numerous relationships between spirality and various environmental and silvicultural conditions. Few of such relationships can be broadly documented, however.

It may be that trees grown at high elevation in harsh climates exhibit more spiral grain than trees grown in a gentler environment—but evidence in the literature is not conclusive. Correlations between width of annual growth rings and angle of spiral grain vary with investigator and are inconclusive, partly because of interaction between tree age and width of growth ring. Some investigators have observed that compression wood contains relatively straight-grained wood. For further comments on these three relationships see the Results section.

Harris (1989) concluded: "there is no support for the belief that regular patterns of spirality can be initiated by, or attributed primarily to, any environmental factor; it seems probable that the propensity for spiral grain is determined by heredity, although its expression may be dependent, at least in part, on the environment. ...Northern trees do not reverse their initial spiral grain direction when grown below the equator."

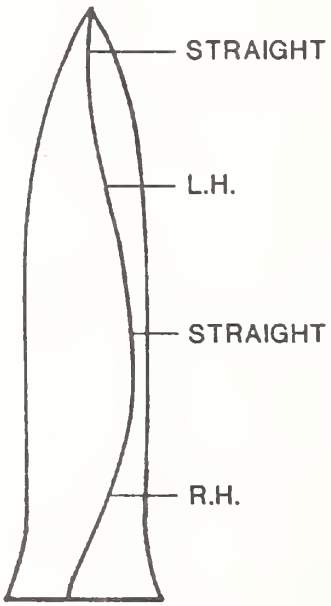



Figure 9—Grain direction along the outside of a stem with spirality pattern common to many conifers, lodgepole pine included. (Drawing after Harris 1989.)

## Effects on Products

Cooper and Ross (1977) concluded from observations in Alberta, Canada, that spiral grain in lodgepole pine utility poles contributes to sapwood rot because resulting spiral checks hold moisture from precipitation longer than vertical checks in straight-grained poles.

Wellner and Lowery (1967) found from a study of spiral grain in coniferous utility poles (including lodgepole pine) that:

> Twisting of poles in service was definitely correlated with spiral grain. Poles with severe left-hand spiral tended to be the bad twisters. Poles with right-hand spiral usually were more stable, with respect to twisting, than straight-grained poles. The cause of this difference was determined to be the internal grain structure. Poles with surface left-hand spiral contained left-hand spiraled grain from the center of the pole out to the surface. Poles with surface right-hand-spiraled grain usually contained left-hand spiraled grain near the pith and right-hand spiraled grain near the surface. The result was counteracting twist forces and little net twist.
>
> Proper seasoning might stabilize poles having severe left-hand spiral and make them satisfactory for use in pole lines.

Unfortunately, they found no method of detecting spiral grain in live trees or unpeeled poles by means of surface characteristics.

Lowery and Erickson (1967) found that severely left-spiraled utility poles have lower bending strength and twist more than do severely right-spiraled poles. Moderately right-spiraled grain with a slope of 1:12 or 1: > 12 has a negligible effect on pole strength. If slope of grain in right-spiraled poles is 1:8 or 1: < 8, such poles may have about 75 percent of the strength of straight-grained poles. Poles with left spiral grain of 1:8 to 1:12 slope, however, may not be more than 50 to 60 percent as strong as comparable straight-grained poles.

Following are data from Lowery and Erickson (1967) on maximum twist in air-dried and green lodgepole pine utility poles with moderate and steep spiral grain, after 6 years upright in the ground at a Libby, MT, test site:

| Degree of spiral grain and seasoning at time of pole erection | Maximum twist | |
|---|---|---|
| | Left spiral | Right spiral |
| | *Degrees* | |
| Steep (1 inch in 16 inches or less) | | |
| Air-dried | 17.8 | 8.2 |
| Green | 42.3 | 15.5 |
| Moderate (1 inch in more than 16 inches) | | |
| Air-dried | 18.6 | 3.4 |
| Green | 21.6 | 6.2 |

Research on the effect of spiral grain on twist of lodgepole pine lumber is less extensive than that on twist on poles. Kotok (1967) concluded from a sample of 119 8-foot logs from the Targhee National Forest in Idaho that "spiral-grained trees can yield many straight studs if manufacturing processes are good."

# GENERAL STUDY PROCEDURE

## Locating and Selecting the 243 *Latifolia* Trees

The sample area spanned from 40 to 60 degrees latitude (inclusive) at 2.5-degree intervals; the width of the sample area was 10 degrees of longitude, with sample area shifting 2.5 degrees west for each 2.5 degrees shift north in latitude (fig. 3). Sample band width was 0.5 degree of latitude on each side of the nominal latitude line; each latitude band was 1 degree deep in the north-south direction (60 nautical miles), and 10 degrees of longitude wide in the east-west direction.

Within each of these nine latitudinal sampling bands, natural unthinned stands were identified with the following constraints: adjacent to road traversable by pickup truck; within boundaries of National or Provincial forests; and containing some more-or-less level benches or flats.

It was found that at least nine such stands could be identified within each sampling band. The identified

stands were ranked by elevation, and then the three highest, the three most intermediate, and the three lowest were selected for sampling. These elevational zones were highest in the south and lowest in the north; elevational zone width was broadest at mid-latitude (fig. 4).

On a bench or flat typical of each of these selected stands, single trees 76 mm, 152 mm, and 228 mm in d.b.h. and free of insects and diseases were taken that in the collector's view typified within-stand trees of these diameters on that bench or flat. Thus 27 *latifolia* trees were taken from each of the nine latitudes—3 diameters x 3 elevations x 3 replications, for a total of 243 trees.

It is important to note that this sampling scheme resulted in selection of 76-, 152-, and 228-mm trees that were of approximately the same age, because most of the stands were of fire origin. Thus, most of the small-diameter trees were suppressed, while the larger trees grew fast.

## Locating and Selecting the 36 *Murrayana* Trees

The sample areas extended from 37½ to 45 degrees latitude at 2.5-degree intervals; trees were sampled at 37½, 40, 42½, and 45 degrees—but only at one longitude per latitude (fig. 3).

The same three constraints on location applied to *latifolia* also applied to *murrayana*, but *murrayana* was sampled only from midelevation, as follows:

| Latitude | Elevation | |
|---|---|---|
| *Degrees* | *Meters* | *Feet* |
| 37½ | 2,402 | 7,880 |
| 40 | 1,676 | 5,499 |
| 42½ | 2,006 | 6,581 |
| 45 | 1,148 | 3,766 |

Thus nine *murrayana* trees were taken from each of the four latitudes—3 diameters x 1 elevation x 3 replications, for a total of 36 trees.

## Field and Laboratory Work

For a complete description of the field work see Koch (1987, p. 9).

**Stem Procedure**—In the field the stem was shorn of branches so that it was complete from 152-mm-high stump to apical tip. By stretching a taut string between the 10- and 70-percent stem levels, the maximum sweep was measured and recorded together with the stem level at which it occurred.

From the 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and apical-tip level of the stem a pair of disks was removed. One disk, 50 mm thick, was bagged in polyethelene for laboratory determination of moisture content and specific gravity; the other, 75 mm thick was air-dried for laboratory determination of additional properties.

Also transported from field to laboratory were two stem sections with bark in place—the first between stem levels 10 and 20 percent, the second between 20 and 30 percent. In the laboratory these two stem sections were debarked and both wood and bark air dried and stored.

In the laboratory the number of annual rings at stump height was recorded, and the characterization disks air dried and stored. Each moisture disk was weighed green, its volume measured by water immersion, and its bark thickness (as measured by diameter tape before and after debarking) recorded. The debarked disk was weighed and its volume recorded. Heartwood was indicated by application of ferric chloride solution (10 g FeCl in 90 g water) and split away from the sapwood, heartwood diameter was measured, and heartwood weight and volume recorded. The ovendry weights of bark, sapwood, and heartwood of each disk were then recorded. Taproot length was measured.

**Determination of Spiral Grain and Width of Annual Rings**—Disks taken at 152-mm stump height, 10, 20, 30, 40, 50, 60, 70, 80, and 90 percent of tree height from stump top to apical tip were longitudinally split with a cleaver and mallet to expose the pith and the angle of grain in the split section relative to the alignment of the pith. The sections had been air-dried (8 to 9 percent moisture content) at the time split and when evaluated for grain spirality.

In each disk the angles of spirality relative to the pith were measured at ⅛, ⅜, ⅝, and ⅞ of radius from pith to cambium. These measurements were taken on one radius of the disk only (because the pith is always eccentric to some degree each split disk had a short and a long radius). Selection of long or short radius for measurement was made randomly with some consideration for clarity of view of spirality and annual ring width, and a notation made of whether short or long was selected.

To make the spirality measurement each disk was clamped, with split surfaces and exposed pith uppermost, in a flat-bottomed vise that could be moved over the ground surface of a large flat gage plate. By positioning the pith of the disk under a pedestal-mounted digital micrometer probe, the pith could be adjusted into a horizontal attitude. The digital micrometer was then used to measure the spirality angle and direction (left- or right-hand) at each of the four observation points.

At each observation point, age from pith and distance from pith were recorded.

Width of annual ring was measured as an average of the four rings most immediately adjacent to each observation point. Additionally, the same measurements were taken at that point along the radius where spirality was greatest.

Each disk was characterized by a number denoting spirality classification according to Lowery's (1966) procedure (fig. 8). Perhaps because spirality measurements were taken relative to the pith (rather than in relation to the geometric axis of the entire stem), a significant proportion of the disks had different spirality direction on short and long radii, so an observation of sameness or difference was recorded.

The other tree and disk measurements (including disk diameter measured with a diameter tape) noted at the end of the introductory section were already on hand in a master computer file.

## Statistical Analysis

Analysis of variance was made in three groupings (table 3): *latifolia* throughout its principal latitudinal range of 40 through 60 degrees; *murrayana* through its primary latitudinal range of 37½ through 45 degrees; and *latifolia* compared to *murrayana* at the three common latitudes of 40, 42½, and 45 degrees.

**Table 3**—Analysis of variance format

| Source | Degrees of freedom |
|---|---|
| ***Latifolia*** | |
| Latitude (L) | 8 |
| Elevation (E) | 2 |
| Diameter (D) | 2 |
| L x E | 16 |
| L x D | 16 |
| E x D | 4 |
| L x E x D | 32 |
| Error | 162 |
| Total | 242 |
| ***Murrayana*** | |
| Latitude | 3 |
| Diameter | 2 |
| L x D | 6 |
| Error | 24 |
| Total | 35 |
| ***Latifolia* compared to *murrayana*** | |
| Variety (V) | 1 |
| Latitude | 2 |
| Diameter | 2 |
| V x L | 2 |
| V x D | 2 |
| L x D | 4 |
| V x L x D | 4 |
| Error | 36 |
| Total | 53 |

Correlations of interest observed in *latifolia* between tree characteristics, including those described in Koch (1987), were also determined.

## RESULTS (AMONG-TREE VARIATION)

This portion of the Results section is concerned only with **among-tree** variation of five properties. For the first, second, fourth, and fifth properties we have tabulated values by variety, latitude, elevational zone, and diameter class (with average, standard deviation and range), accompanied by analyses of variance of varieties separately. Also we have compared the two varieties by total sample populations as well as at the three latitudes sampled in common (40, 42.5, and 45 degrees). The third property is more generally described.

The first property is a single spiral-grain value for each tree. No value is entirely satisfactory, but in the small-diameter stems characteristic of lodgepole pine the maximum degree of spirality at each level sampled dominates most wood mechanical properties at that level. If we use this maximum value to characterize the disk, then by appropriately weighting each disk by the volume it represents in the tree, we can get a number (degrees) characterizing the tree—without regard to direction (sign) of grain spirality, calculated as follows:

$$\frac{\text{max. angle at 0\% height} \times D_0^2 + \text{max. angle at 10\% ht} \times D_{0.1}^2 + +++}{D_0^2 + D_{0.1}^2 + +++++++ D_{0.9}^2} \quad (1)$$

where $D$ equals the disk diameter (bark-free and measured by diameter tape) at the stem level indicated by the subscript.

The second property is the prevalence of right-handedness in **maximum values** calculated as a percentage of the 10 disks per tree—that is, if three of the 10 disks had right-hand spirals at the point of maximum spirality, the recorded entry would be 30 percent.

The third property describes the percentages of the 10 disks in each tree displaying patterns 1, 1A, and 3 (the most prevalent patterns; see fig. 8).

The fourth property is the percentage of height in each tree where the maximum degree of spirality was found.

The fifth property is that of tree-average growth-ring width in millimeters. From the bark-free diameter (by diameter tape) of each disk, and the disk age, the following calculation yields a weighted average representative of the entire stem:

$$\frac{0.5(D_0^3/\text{age of disk 0} + D_{0.1}^3/\text{age of disk 0.1} + +++ D_{0.9}^3/\text{age of disk 0.9})}{D_0^2 + D_{0.1}^2 + +++++++ D_{0.9}^2} \quad (2)$$

For *latifolia* only, tree-average degree of spirality, tree percentage of right-handedness in maximum

values of spiral grain, and tree-average growth-ring width were correlated with a wide variety of other properties characterizing each tree.

## Tree-Average Spiral Grain Value

***Latifolia***—The tree-average volume-weighted value for maximum spiral grain (table 4) varied significantly with tree d.b.h. (large trees had greater spirality than small trees) as follows:

| Tree d.b.h. | Tree-average spirality |
|---|---|
| *mm* | *Degrees* |
| 76 | 3.61 |
| 152 | 4.14 |
| 228 | 4.79 |

It also varied significantly with latitude. Spirality was greatest in southernmost and northernmost latitudes, and least in mid-latitudes, as follows:

| Latitude | Tree-average spirality |
|---|---|
| *Degrees* | *Degrees* |
| 40 | 4.89 |
| 42.5 | 4.08 |
| 45 | 3.99 |
| 47.5 | 3.75 |
| 50 | 3.94 |
| 52.5 | 3.52 |
| 55 | 3.91 |
| 57.5 | 4.81 |
| 60 | 4.76 |
| Average | 4.18 |

Tree-average spirality did not vary significantly with elevational zone.

**Correlations**—In *latifolia*, tree-average volume-weighted maximum spiral grain angle had significant correlation (0.05 level) with many other tree characteristics, as follows:

| Characteristic | Positive *r* | Negative *r* |
|---|---|---|
| Tree age at 152-mm stump height | 0.451 | |
| Stemwood taper within live crown, millimeter/meter | .433 | |
| Average live-branch diameter | .417 | |
| Heartwood diameter at 152-mm stump height | .381 | |
| Tree-average pith eccentricity in stem, millimeter | .373 | |
| D.b.h. | .352 | |
| Stemwood diameter at 152-mm stump height | .350 | |
| Live branch weight, ovendry | .322 | |
| Total stump-root weight with bark, ovendry | .307 | |
| Stemwood diameter at base of live crown | .303 | |
| Total number of cones on first foot of top 25 branches | .298 | |
| Width of live crown | .285 | |
| Foliage weight, ovendry | .283 | |
| Complete-tree weight, ovendry | .281 | |
| Stem heartwood weight, ovendry | .272 | |
| Branch bark thickness | .263 | |
| Total stem weight with bark, ovendry | .257 | |
| Total stemwood weight, ovendry | .256 | |
| Stembark moisture content, percent of ovendry weight | | –0.249 |
| Stemwood taper to base of live crown, millimeter/meter | .247 | |
| Branchwood percent of complete-tree weight, ovendry | .224 | |
| Bark percent of complete-tree weight, ovendry | | –.219 |
| Stembark specific gravity | .218 | |
| Dead branch weight, ovendry | .217 | |
| Stem sapwood weight, ovendry | .213 | |
| Number of dead branches | .207 | |
| Percent of tree height at maximum spirality | | –.199 |
| Cone percentage of complete-tree weight, ovendry | .187 | |
| Maximum stem crook | .185 | |
| Complete-tree moisture content, percent of ovendry weight | | –.184 |
| Heartwood moisture content, percent of ovendry weight | | –.183 |
| Stump bark average thickness | .183 | |
| Tree height to apical tip | .169 | |
| Foliage percent of complete-tree weight, ovendry | | –.157 |
| Stemwood moisture content, percent of ovendry weight | | –.156 |

Also of interest was the lack of significant correlation with average annual ring width at 152-mm-height stump top, volume-weighted tree-average ring width, tree-average percent compression wood, or with volume-weighted tree-average fiber length.

In summary, when evaluating entire stems of *latifolia* trees, greatest tree-average spirality was found in old, large-diameter, heavy trees with heavy stump-root systems, much heartwood and eccentric piths in stems, many cones, and long wide crowns comprised of many thick-barked large-diameter branches bearing much foliage. Spirality tends to be greater in extreme north and south latitudes than at midlatitudes of the species' range. In the 243 *latifolia* trees examined, variation was substantial; volume-weighted, tree-average maximum spiral grain ranged from 1.5 degrees to 10.7 degrees.

***Murrayana* vs. *Latifolia***—Tree-average volume-weighted maximum degree of spirality did not vary significantly between entire populations sampled from the two varieties. The average for *murrayana*

**Table 4**—Mean, standard deviation, and range of tree-average volume-weighted maximum spiral grain angle for *latifolia* by latitude, elevational zone, and tree d.b.h.[1]

| Elevation | Tree d.b.h. 76 mm | 152 mm | 228 mm | All trees |
|---|---|---|---|---|
| | | *Degrees* | | |
| | | **40 degrees latitude** | | |
| Low | 4.42(0.8) | 5.06(1.2) | 4.54(0.5) | 4.67(0.8) |
| | 3.5-4.9 | 3.8-6.3 | 4.1-5.1 | 3.5-6.3 |
| Medium | 3.77(0.9) | 4.23(0.9) | 5.26(1.6) | 4.42(1.2) |
| | 2.7-4.6 | 3.2-4.9 | 4.0-7.1 | 2.7-7.1 |
| High | 3.59(1.3) | 5.24(3.7) | 7.89(2.5) | 5.57(3.0) |
| | 2.7-5.0 | 2.8-9.4 | 5.8-10.7 | 2.7-10.7 |
| | | **42.5 degrees latitude** | | |
| Low | 2.38(0.2) | 4.17(0.8) | 3.82(1.5) | 3.46(1.2) |
| | 2.1-2.6 | 3.5-5.1 | 2.1-4.8 | 2.1-5.1 |
| Medium | 3.00(0.4) | 4.78(0.7) | 5.20(1.0) | 4.32(1.2) |
| | 2.5-3.4 | 4.1-5.5 | 4.1-6.1 | 2.5-6.1 |
| High | 3.46(1.3) | 4.50(0.8) | 5.44(3.3) | 4.47(2.0) |
| | 2.2-4.8 | 3.7-5.2 | 3.3-9.2 | 2.2-9.2 |
| | | **45 degrees latitude** | | |
| Low | 2.72(1.7) | 3.34(1.8) | 4.21(1.4) | 3.42(1.6) |
| | 1.5-4.7 | 2.2-5.4 | 3.2-5.8 | 1.5-5.8 |
| Medium | 4.25(1.3) | 3.43(1.0) | 5.85(1.2) | 4.51(1.5) |
| | 2.8-5.2 | 2.4-4.2 | 4.6-7.0 | 2.4-7.0 |
| High | 3.30(0.3) | 3.85(1.4) | 4.99(1.2) | 4.05(1.2) |
| | 3.0-3.6 | 2.3-4.8 | 3.7-6.1 | 2.3-6.1 |
| | | **47.5 degrees latitude** | | |
| Low | 3.47(0.1) | 3.96(0.7) | 4.01(0.4) | 3.81(0.5) |
| | 3.4-3.6 | 3.3-4.7 | 3.6-4.4 | 3.3-4.7 |
| Medium | 2.79(1.0) | 3.91(0.8) | 3.74(1.2) | 3.50(1.0) |
| | 2.1-3.9 | 3.2-4.7 | 2.4-4.8 | 2.1-4.8 |
| High | 3.64(0.8) | 3.79(0.7) | 4.44(1.9) | 3.96(1.1) |
| | 3.1-4.6 | 3.0-4.3 | 3.3-6.6 | 3.0-6.6 |
| | | **50 degrees latitude** | | |
| Low | 3.02(0.6) | 2.54(0.9) | 4.85(1.2) | 3.47(1.3) |
| | 2.7-3.7 | 2.0-3.6 | 3.4-5.7 | 2.0-5.7 |
| Medium | 3.20(0.5) | 4.66(0.4) | 5.09(0.2) | 4.30(0.9) |
| | 2.7-3.6 | 4.3-5.0 | 4.9-5.2 | 2.7-5.2 |
| High | 3.44(1.3) | 4.27(1.0) | 4.44(2.3) | 4.05(1.5) |
| | 2.5-4.9 | 3.2-5.2 | 2.7-7.1 | 2.5-7.1 |
| | | **52.5 degrees latitude** | | |
| Low | 2.78(0.2) | 2.93(0.9) | 4.02(0.6) | 3.25(0.8) |
| | 2.6-2.9 | 2.2-3.9 | 3.4-4.6 | 2.2-4.6 |
| Medium | 2.91(0.4) | 3.93(1.6) | 4.63(0.8) | 3.82(1.2) |
| | 2.6-3.3 | 2.3-5.4 | 3.8-5.5 | 2.3-5.5 |
| High | 3.16(1.0) | 3.46(1.2) | 3.82(0.5) | 3.48(0.9) |
| | 2.4-4.3 | 2.7-4.8 | 3.4-4.4 | 2.4-4.8 |
| | | **55 degrees latitude** | | |
| Low | 4.18(2.1) | 4.75(1.3) | 4.18(1.0) | 4.37(1.4) |
| | 2.6-6.5 | 3.3-5.8 | 3.4-5.4 | 2.6-6.5 |
| Medium | 4.00(0.7) | 3.84(0.9) | 3.34(0.3) | 3.73(0.7) |
| | 3.5-4.8 | 3.1-4.8 | 3.1-3.6 | 3.1-4.8 |
| High | 2.92(0.5) | 4.03(0.4) | 3.91(1.5) | 3.62(1.0) |
| | 2.5-3.4 | 3.6-4.4 | 2.5-5.4 | 2.5-5.4 |
| | | **57.5 degrees latitude** | | |
| Low | 4.60(1.1) | 5.00(1.5) | 4.70(1.5) | 4.77(1.2) |
| | 3.7-5.9 | 3.7-6.6 | 3.6-6.4 | 3.6-6.6 |
| Medium | 4.11(0.6) | 5.43(0.8) | 5.40(1.1) | 4.98(1.0) |
| | 3.7-4.7 | 4.5-6.1 | 4.6-6.6 | 3.7-6.6 |
| High | 5.00(0.5) | 3.49(2.3) | 5.52(0.9) | 4.67(1.6) |
| | 4.4-5.4 | 1.6-6.0 | 4.4-6.1 | 1.6-6.1 |
| | | **60 degrees latitude** | | |
| Low | 3.56(0.7) | 4.12(1.4) | 5.35(0.9) | 4.34(1.2) |
| | 3.1-4.3 | 2.7-5.4 | 4.6-6.3 | 2.7-6.3 |
| Medium | 4.31(0.9) | 4.57(0.5) | 5.00(0.5) | 4.61(0.6) |
| | 3.5-5.3 | 4.2-5.1 | 4.7-5.5 | 3.5-5.5 |
| High | 5.58(1.4) | 4.56(0.7) | 5.83(2.1) | 5.32(1.4) |
| | 4.7-7.2 | 3.9-5.2 | 4.0-8.1 | 3.9-8.1 |
| Pooled | 3.61(1.1) | 4.14(1.3) | 4.79(1.5) | 4.18(1.4) |
| | 1.5-7.2 | 1.6-9.4 | 2.1-10.7 | 1.5-10.7 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 243, that is, 27 per latitude.

(table 5) was 4.57 degrees, with standard deviation of 1.34 degrees; that for *latifolia* was 4.18 degrees, with standard deviation of 1.37 degrees. Neither did the varieties differ significantly when compared only at the three latitudes the variety samples had in common.

By analysis of variance, *murrayana* trees showed no significant differences in degree of spirality with either latitude or d.b.h. (table 5). Averages by d.b.h. were as follows:

| Tree d.b.h. | Tree-average spirality |
|---|---|
| *mm* | *Degrees* |
| 76 | 4.00 |
| 152 | 4.61 |
| 228 | 5.11 |

## Tree Percentages of Right-Handedness in Maximum Values of Spiral Grain Observed in Ten Disks From Each Tree

***Latifolia***—Trees had great variation in the percentage of disks that displayed right-hand spiral grain at the point of maximum spiral grain (table 6); the average for the 243 trees was 26.0 percent with standard deviation of 24.1 percent and range from 0 to 100 percent. This variability made trends difficult to discern. By analysis of variance, percentages did not vary significantly with latitude, elevational zone, or d.b.h. By simple correlation from observations of the 243 *latifolia* trees some weak trends were discernible, however. Percentage of right-handedness was positively correlated with latitude ($r = 0.1836$; $p = 0.004$), that is, the two southern latitudes had less than 19 percent and the northernmost latitude had 35 percent, as follows:

| Latitude | Percentage of right-handedness |
|---|---|
| *Degrees* | *Percentage of 10 disks/tree* |
| 40 | 18.9 |
| 42.5 | 15.6 |
| 45 | 25.6 |
| 47.5 | 28.1 |
| 50 | 28.5 |
| 52.5 | 27.4 |
| 55 | 28.5 |
| 57.5 | 26.3 |
| 60 | 35.2 |

Tree d.b.h. had very weak positive correlation with percentage of right-handedness ($r = 0.1142$; $p = 0.076$); each value in the following tabulation represents 81 trees:

| Tree d.b.h. | Percentage of right-handedness |
|---|---|
| *mm* | *Percentage of 10 disks/tree* |
| 76 | 22.7 |
| 152 | 25.9 |
| 228 | 29.4 |

Absolute elevation (m) proved to be negatively correlated with percentage of right-handedness ($r = 0.1262$; $p = 0.049$). Elevation (m) is confounded by latitude, however. That is, elevation of sampled trees diminished with increasing latitude (fig. 4), so that elevation's apparently negative effect may be

Table 5—Mean, standard deviation, and range of tree-average volume-weighted maximum spiral grain for *murrayana* by latitude and tree d.b.h.[1]

| Latitude | Tree d.b.h 76 mm | 152 mm | 228 mm | All trees |
|---|---|---|---|---|
| *Degrees* | *Spiral grain, degrees* | | | |
| 37.5 | 3.91(2.2) | 4.86(0.8) | 4.97(1.6) | 4.58(1.5) |
| | 2.3-6.4 | 4.0-5.6 | 3.5-6.7 | 2.3-6.7 |
| 40 | 3.44(1.4) | 3.98(1.1) | 5.37(1.3) | 4.27(1.4) |
| | 2.0-4.9 | 2.8-4.9 | 3.9-6.3 | 2.0-6.3 |
| 42.5 | 4.28(1.5) | 6.02(1.6) | 5.21(1.6) | 5.17(1.5) |
| | 3.0-5.9 | 4.9-7.9 | 4.1-7.0 | 3.0-7.9 |
| 45 | 4.38(0.8) | 3.58(0.9) | 4.88(0.2) | 4.28(0.8) |
| | 0.4-1.1 | 0.8-2.4 | 1.3-3.0 | 0.4-3.0 |
| Pooled | 4.00(1.4) | 4.61(1.4) | 5.11(1.1) | 4.57(1.3) |
| | 2.0-6.4 | 2.6-7.9 | 3.5-7.0 | 2.0-7.9 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 36, that is, nine per latitude.

**Table 6**—Mean, standard deviation, and range of percentages of right-handedness in maximum values of spiral grain observed in 10 disks from each *latifolia* tree, by latitude, elevational zone, and tree d.b.h.[1]

| Elevation | Tree d.b.h. 76 mm | 152 mm | 228 mm | All trees |
|---|---|---|---|---|
| | | *Percent* | | |
| | | **40 Degrees latitude** | | |
| Low | 3.3(5.8) | 33.3(41.6) | 10.0(17.3) | 15.6(26.5) |
| | 0-10 | 0-80 | 0-30 | 0-80 |
| Medium | 40.0(40.0) | 10.0(10.0) | 10.0(17.3) | 20.0(26.9) |
| | 0-80 | 0-20 | 0-30 | 0-80 |
| High | 33.3(40.4) | 16.7(20.8) | 13.3(15.3) | 21.1(25.7) |
| | 10-80 | 0-40 | 0-30 | 0-80 |
| | | **42.5 Degrees latitude** | | |
| Low | 13.3(5.8) | 20.0(26.5) | 13.3(5.8) | 15.6(14.2) |
| | 10-20 | 0-50 | 10-20 | 0-50 |
| Medium | 26.7(20.8) | 3.3(5.8) | 23.3(23.1) | 17.8(19.2) |
| | 10-50 | 0-10 | 10-50 | 0-50 |
| High | 20.0(0) | 10.0(10.0) | 10.0(10.0) | 13.3(8.7) |
| | 20-20 | 0-20 | 0-20 | 0-20 |
| | | **45 Degrees latitude** | | |
| Low | 13.3(15.3) | 16.7(15.3) | 20.0(10.0) | 16.7(12.2) |
| | 0-30 | 0-30 | 10-30 | 0-30 |
| Medium | 10.0(10.0) | 30.0(10.0) | 46.7(30.6) | 28.9(23.2) |
| | 0-20 | 20-40 | 20-80 | 0-80 |
| High | 43.3(20.8) | 23.3(11.5) | 26.7(15.3) | 31.1(16.9) |
| | 20-60 | 10-30 | 10-40 | 10-60 |
| | | **47.5 Degrees latitude** | | |
| Low | 6.7(11.5) | 13.3(15.3) | 43.3(23.1) | 21.1(22.6) |
| | 0-20 | 0-30 | 30-70 | 0-70 |
| Medium | 10.0(0) | 40.0(26.5) | 36.7(25.2) | 28.9(23.2) |
| | 10-10 | 10-60 | 10-60 | 10-60 |
| High | 10.0(10.0) | 46.7(20.8) | 46.7(35.1) | 34.4(27.9) |
| | 0-20 | 30-70 | 10-80 | 0-80 |
| | | **50 Degrees latitude** | | |
| Low | 16.7(20.8) | 36.7(20.8) | 46.7(41.6) | 33.3(28.7) |
| | 0-40 | 20-60 | 0-80 | 0-80 |
| Medium | 13.3(15.3) | 26.7(37.9) | 3.3(5.8) | 14.4(23.0) |
| | 0-30 | 0-70 | 0-10 | 0-70 |
| High | 46.7(20.8) | 43.3(41.6) | 23.3(20.8) | 37.8(27.7) |
| | 30-70 | 10-90 | 0-40 | 0-90 |
| | | **52.5 Degrees latitude** | | |
| Low | 23.3(40.4) | 20.0(17.3) | 36.7(46.2) | 26.7(32.8) |
| | 0-70 | 10-40 | 10-90 | 0-90 |
| Medium | 26.7(11.5) | 20.0(20.0) | 60.0(34.6) | 35.6(27.9) |
| | 20-40 | 0-40 | 20-80 | 0-80 |
| High | 10.0(0) | 26.7(30.6) | 23.3(25.2) | 20.0(21.2) |
| | 10-10 | 0-60 | 0-50 | 0-60 |
| | | **55 Degrees latitude** | | |
| Low | 13.3(15.3) | 46.7(40.4) | 33.3(41.6) | 31.1(33.3) |
| | 0-30 | 10-90 | 0-80 | 0-90 |
| Medium | 6.7(11.5) | 10.0(10.0) | 50.0(10.0) | 22.2(22.8) |
| | 0-20 | 0-20 | 40-60 | 0-60 |
| High | 43.3(5.8) | 30.0(17.3) | 23.3(25.2) | 32.2(17.9) |
| | 40-50 | 10-40 | 0-50 | 0-50 |
| | | **57.5 Degrees latitude** | | |
| Low | 13.3(15.3) | 6.7(5.8) | 13.3(11.5) | 11.1(10.5) |
| | 0-30 | 0-10 | 0-20 | 0-30 |
| Medium | 20.0(17.3) | 40.0(30.0) | 56.7(51.3) | 38.9(34.8) |
| | 10-40 | 10-70 | 0-100 | 0-100 |
| High | 26.7(20.8) | 26.7(15.3) | 33.3(25.2) | 28.9(18.3) |
| | 10-50 | 10-40 | 10-60 | 10-60 |
| | | **60 Degrees latitude** | | |
| Low | 36.7(25.2) | 43.3(15.3) | 30.0(26.5) | 36.7(20.6) |
| | 10-60 | 30-60 | 10-60 | 10-60 |
| Medium | 26.7(15.3) | 20.0(20.0) | 10.0(10.0) | 18.9(15.4) |
| | 10-40 | 0-40 | 0-20 | 0-40 |
| High | 60.0(30.0) | 40.0(20.0) | 50.0(26.5) | 50.0(24.0) |
| | 30-90 | 20-60 | 30-80 | 20-90 |
| Pooled | 22.7(21.8) | 25.9(22.9) | 29.4(27.0) | 26.0(24.1) |
| | 0-90 | 0-90 | 0-100 | 0-100 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 243, that is, 27 per latitude.

partially or wholly attributable to latitude. This interpretation is reinforced by elevational zonal data based on 81 trees per zone, as follows:

| Elevational zone | Percentage of right-handedness |
|---|---|
| | *Percentage of 10 disks per tree* |
| Low | 23.1 |
| Medium | 25.1 |
| High | 29.9 |

**Correlations**—In addition to the correlations with latitude and elevation, the percentage of right-handedness had significant (0.05 level) correlation with many other *latifolia* tree characteristics, as follows:

| Characteristic | Positive *r* | Negative *r* |
|---|---|---|
| Tree age at 152-mm stump height | 0.317 | |
| Stembark specific gravity | .220 | |
| Volume-weighted tree-average growth ring width | | –0.200 |
| Heartwood diameter at 152-mm stump height | .200 | |
| Heartwood weight in stem, ovendry | .197 | |
| Average diameter of live branches | .177 | |
| Stump-average bark thickness | .171 | |
| Complete-tree moisture content, percent of ovendry weight | | –.168 |
| Stembark moisture content, percent of ovendry weight | | –.160 |
| Stemwood taper within live crown, millimeters/meter | .158 | |
| Longitude, degrees | .155 | |
| Stembark thickness at 152-mm stump height | .155 | |
| Stemwood moisture content, percent of ovendry weight | | –.152 |
| Tree-average pith eccentricity in stem, millimeters | .145 | |
| Average annual ring width at 152-mm stump height | | –.142 |
| Heartwood moisture content, percent of ovendry weight | | –.138 |
| Total stem weight with bark, ovendry | .129 | |
| Volume-weighted stemwood-average fiber length | | –.128 |

Also of interest was the lack of significant correlation with tree-average percent compression wood, foliage weight, or crown size. Volume-weighted stemwood-average fiber length had a very weak but statistically significant negative correlation with percentage of right-handedness.

In summary, when evaluating entire stems of *latifolia* trees, greatest percentage of right-handedness at point of maximum spiral grain in 10 sections sampled in each stem was found in slow-growing old trees with large live branches, dense stembark, thick stump bark, and with heavy stems having eccentric piths and large heartwood diameter at stump height. Wood and bark of such trees tend to be low in percentage moisture content.

Also, percentage of right-handedness tended to be greater (35.2 percent) at the northernmost latitude of *latifolia* sampled—60 degrees—than in the southernmost latitudes of 40 and 42.5 degrees (average of 17.3 percent). In the 243 *latifolia* trees examined, variation was extreme; percentage of right-handedness in maximum values of spiral grain ranged from 0 to 100 percent.

***Murrayana* vs. *Latifolia***—Tree-average percentage of right-handedness of maximum spirality did not vary significantly between entire populations sampled from the two varieties. The average for *murrayana* (table 7) was 26.7 percent, with standard deviation of 21.2 percent; that for *latifolia* (table 6) was 26.0 percent, with standard deviation of 24.1 percent. Neither did the varieties differ significantly when compared only at the three latitudes the variety samples had in common.

By analysis of variance, *murrayana* trees showed no significant differences in percentage of right-handedness with either latitude or d.b.h. (table 7).

## Percentage of Height in Each Tree Where Maximum Spirality Was Observed

***Latifolia***—There was wide variation in the percentage of height in each tree where the maximum degree of spirality (sign ignored) was observed, so trends were hard to discern. The height of maximum spirality averaged 41.0 percent of tree height, with standard deviation of 30.5 percent and range from 0 to 90 percent (table 8). Analysis of variance indicated no significant differences associated with tree d.b.h., elevational zone, or latitude. Simple correlation with latitude was significant, however ($r = 0.150$; $p = 0.019$). Means (27 trees) for latitudinal zones varied from 31 percent to 55 percent, as follows:

| Latitude | Height of maximum spirality |
|---|---|
| *Degrees* | *Percent of tree height* |
| 40 | 36.3 |
| 42.5 | 36.3 |
| 45 | 38.5 |
| 47.5 | 31.1 |
| 50 | 46.7 |
| 52.5 | 42.6 |
| 55 | 42.9 |
| 57.5 | 39.6 |
| 60 | 55.2 |

**Table 7**—Mean, standard deviation, and range of percentages of right-handedness in maximum values of spiral grain observed in 10 disks from each *murrayana* tree, by latitude and tree d.b.h.[1]

| Latitude | Tree d.b.h 76 mm | Tree d.b.h 152 mm | Tree d.b.h 228 mm | All trees |
|---|---|---|---|---|
| *Degrees* | | *Percent* | | |
| 37.5 | 6.7(11.5) | 33.5(15.3) | 13.3(15.3) | 17.8(17.2) |
| | 0-20 | 20-50 | 0-30 | 0-50 |
| 40 | 43.3(20.8) | 30.0(17.3) | 13.3(11.5) | 28.9(19.7) |
| | 20-60 | 10-40 | 0-20 | 0-60 |
| 42.5 | 33.3(23.1) | 33.3(35.1) | 13.3(11.5) | 26.7(24.0) |
| | 20-60 | 0-70 | 0-20 | 0-70 |
| 45 | 40.0(34.6) | 30.0(30.0) | 30.0(10.0) | 33.3(24.0) |
| | 20-80 | 0-60 | 20-40 | 0-80 |
| Pooled | 30.8(25.4) | 31.7(22.1) | 17.5(12.9) | 26.7(21.2) |
| | 0-80 | 0-70 | 0-40 | 0-80 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 36, that is, 9 per latitude.

In *latifolia* there was little correlation between tree properties and percentage of height in each tree where maximum spirality occurred. Apart from latitude, only volume-weighted tree-average degree of spiral grain was significantly correlated with this percentage ($r = -0.199$; $p = 0.002$). Thus the point of maximum spirality tended to be lowest in stems sampled from southerly latitudes and from trees with a high degree of average spirality. Neither stemwood-average compression wood content nor stemwood-average fiber length were significantly correlated with height of maximum spirality.

***Murrayana* vs. *Latifolia***—In the entire population of variety *murrayana* sampled (table 9) the percentage of tree height at which the maximum degree of spirality was observed averaged significantly less (24.7 percent) than in the entire population of *latifolia* sampled (41.0 percent). In both varieties the standard deviation was 30.5 percent.

Trees sampled from the three latitudes the two varieties had in common (40, 42.5, and 45 degrees) also differed in height of maximum spirality; *murrayana* from these latitudes averaged 21.5 percent, whereas *latifolia* averaged 50.0 percent of tree height.

Percentage of height in *murrayana* did not differ significantly with either latitude or tree d.b.h. (table 9).

Frequency distribution (fig. 10) illustrates not only varietal differences, but also the wide distribution of values. Maximum spirality occurred most frequently not at average values but at 152-mm-high stump top for both varieties, with a second and lesser concentration of maximum spirality at 70 percent of tree height in *latifolia* and 80 percent in *murrayana*.

The maximum spirality at stump height tends to be right-hand near the bark—particularly in large trees (fig. 11D), whereas maximum spirality in upper stem sections tends to be left-hand (fig. 11B).

## Percentages of the 10 Disks in Each Tree Displaying the 13 Patterns Defined in Figure 8

With data for all trees pooled by variety, patterns 1, 1A, and 3 (figs. 8 and 11) dominated, accounting for 78.4 percent of the tree-average patterns in *latifolia* and 82.2 percent in *murrayana*. Virtually all trees had some degree of spirality (table 10).

As we classified pattern 2A (fig. 8), it also included sections in which grain spirality crossed from left-hand to right-hand for a few years, but later returned to left-hand spirality. As we classified pattern 6A, it also included sections in which grain spirality crossed from right-hand to left-hand for a few years, but later returned to right-hand spirality. In pattern 3 as we observed it, spiral grain may attain a left-hand maximum away from the pith before changing to a right-hand spiral.

**Pattern #1—*Latifolia*** —With data from all 243 trees pooled, 17.1 percent of the disks in each tree displayed pattern 1, with standard deviation of 15.6 percent and range from 0 to 90 percent of the disks in each tree. Prevalence of pattern 1 (left-hand with increasing left-hand spirality away from the pith) was significantly greater in trees 76 mm in d.b.h. (22.5 percent) than in those 152 mm or 228 mm in d.b.h. (14.3 and 14.6 percent, respectively);

**Table 8**—Mean, standard deviation, and range of height where maximum spiral grain occurs in *latifolia* trees, by latitude, elevational zone, and tree d.b.h.[1]

| Elevation | Tree d.b.h. 76 mm | 152 mm | 228 mm | All trees |
|---|---|---|---|---|
| | *Percent of tree height* | | | |
| | **40 degrees latitude** | | | |
| Low | 30.0(43.6) | 20.0(26.5) | 33.3(23.1) | 27.8(28.6) |
| | 0-80 | 0-50 | 20-60 | 0-80 |
| Medium | 53.3(25.2) | 63.3(23.1) | 46.7(40.4) | 54.4(27.4) |
| | 30-80 | 50-90 | 10-90 | 10-90 |
| High | 30.0(43.6) | 6.7(5.8) | 43.3(41.6) | 26.7(34.3) |
| | 0-80 | 0-10 | 10-90 | 0-90 |
| | **42.5 degrees latitude** | | | |
| Low | 36.7(37.9) | 46.7(25.2) | 56.7(20.8) | 46.7(26.5) |
| | 10-80 | 20-70 | 40-80 | 10-80 |
| Medium | 30.0(52.0) | 33.3(25.2) | 56.7(15.3) | 40.0(32.4) |
| | 0-90 | 10-60 | 40-70 | 0-90 |
| High | 63.3(23.1) | 3.3(5.8) | 0.0(0.0) | 22.2(33.1) |
| | 50-90 | 0-10 | 0-0 | 0-90 |
| | **45 degrees latitude** | | | |
| Low | 56.7(49.3) | 26.7(46.2) | 36.7(35.1) | 40.0(40.3) |
| | 0-90 | 0-80 | 0-70 | 0-90 |
| Medium | 70.0(10.0) | 40.0(40.0) | 56.7(15.3) | 55.6(25.6) |
| | 60-80 | 0-80 | 40-70 | 0-80 |
| High | 33.3(41.6) | 3.3(5.8) | 23.3(20.8) | 20.0(26.9) |
| | 0-80 | 0-10 | 0-40 | 0-80 |
| | **47.5 degrees latitude** | | | |
| Low | 13.3(15.3) | 16.7(28.9) | 30.0(20.0) | 20.0(20.6) |
| | 0-30 | 0-50 | 10-50 | 0-50 |
| Medium | 46.7(41.6) | 43.3(20.8) | 46.7(41.6) | 45.6(31.3) |
| | 0-80 | 20-60 | 0-80 | 0-80 |
| High | 46.7(35.1) | 13.3(15.3) | 23.3(23.1) | 27.8(26.8) |
| | 10-80 | 0-30 | 10-50 | 0-80 |
| | **50 degrees latitude** | | | |
| Low | 50.0(45.8) | 63.3(11.5) | 36.7(35.1) | 50.0(31.6) |
| | 0-90 | 50-70 | 0-70 | 0-90 |
| Medium | 43.3(40.4) | 33.3(30.6) | 56.7(23.1) | 44.4(29.6) |
| | 0-80 | 0-60 | 30-70 | 0-80 |
| High | 50.0(45.8) | 33.3(30.6) | 53.3(30.6) | 45.6(32.8) |
| | 0-90 | 0-60 | 20-80 | 0-90 |
| | **52.5 degrees latitude** | | | |
| Low | 30.0(36.1) | 63.3(20.8) | 83.3(11.5) | 58.9(31.8) |
| | 0-70 | 40-80 | 70-90 | 0-90 |
| Medium | 20.0(20.0) | 30.0(30.0) | 26.7(25.2) | 25.6(22.4) |
| | 0-40 | 0-60 | 0-50 | 0-60 |
| High | 26.7(25.2) | 43.3(15.3) | 60.0(20.0) | 43.3(22.9) |
| | 0-50 | 30-60 | 40-80 | 0-80 |
| | **55 degrees latitude** | | | |
| Low | 30.0(26.5) | 33.3(15.3) | 36.7(40.4) | 33.3(25.5) |
| | 0-50 | 20-50 | 0-80 | 0-80 |
| Medium | 53.3(15.3) | 53.3(25.2) | 76.7(15.3) | 61.1(20.3) |
| | 40-70 | 30-80 | 60-90 | 30-90 |
| High | 40.0(43.6) | 6.7(11.5) | 56.7(49.3) | 34.4(40.0) |
| | 10-90 | 0-20 | 0-90 | 0-90 |
| | **57.5 degrees latitude** | | | |
| Low | 46.7(25.2) | 6.7(11.5) | 53.3(20.8) | 35.6(27.9) |
| | 20-70 | 0-20 | 30-70 | 0-70 |
| Medium | 56.7(15.3) | 53.3(25.2) | 13.3(23.1) | 41.1(28.0) |
| | 40-70 | 30-80 | 0-40 | 0-80 |
| High | 50.0(36.1) | 53.3(30.6) | 23.3(23.1) | 42.2(29.9) |
| | 10-80 | 20-80 | 10-50 | 10-80 |
| | **60 degrees latitude** | | | |
| Low | 53.3(23.1) | 53.3(47.3) | 66.7(40.4) | 57.8(33.8) |
| | 40-80 | 0-90 | 20-90 | 0-90 |
| Medium | 50.0(36.1) | 60.0(43.6) | 46.7(11.5) | 52.2(29.5) |
| | 10-80 | 10-90 | 40-60 | 10-90 |
| High | 60.0(17.3) | 76.7(15.3) | 30.0(26.5) | 55.6(27.0) |
| | 50-80 | 60-90 | 0-50 | 0-90 |
| Pooled | 43.3(31.4) | 36.3(30.1) | 43.5(29.8) | 41.0(30.5) |
| | 0-90 | 0-90 | 0-90 | 0-90 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 243, that is, 27 per latitude.

**Table 9**—Mean, standard deviation, and range of height where maximum spiral grain occurs in *murrayana* trees, by latitude and tree d.b.h.[1]

| Latitude | Tree d.b.h. | | | All trees |
|---|---|---|---|---|
| | 76 mm | 152 mm | 228 mm | |
| *Degrees* | *Percent of tree height* | | | |
| 37.5 | 46.7(40.4) | 13.3(15.3) | 43.3(40.4) | 34.4(33.6) |
| | 0-70 | 0-30 | 0-80 | 0-80 |
| 40 | 10.0(17.3) | 10.0(10.0) | 6.7(11.5) | 8.9(11.7) |
| | 0-30 | 0-20 | 0-20 | 0-30 |
| 42.5 | 3.3(5.8) | 26.7(46.2) | 43.3(40.4) | 24.4(35.4) |
| | 0-10 | 0-80 | 0-80 | 0-80 |
| 45 | 46.7(40.4) | 46.7(25.2) | 0.0(0.0) | 31.1(33.3) |
| | 0-70 | 20-70 | 0-0 | 0-70 |
| Pooled | 26.7(33.1) | 24.2(28.1) | 23.3(32.6) | 24.7(30.5) |
| | 0-70 | 0-80 | 0-80 | 0-80 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 36, that is, 9 per latitude .

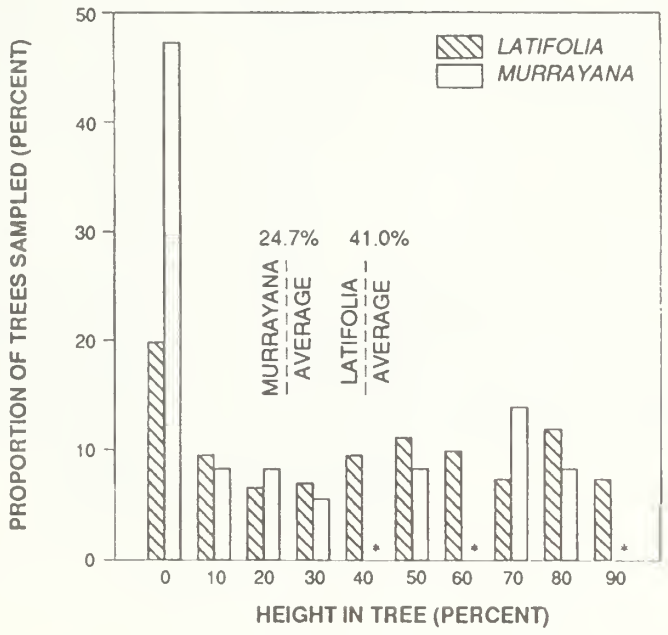



**Figure 10**—Frequency distribution of height in trees of both varieties (entire populations sampled, that is, 243 *latifolia* and 36 *murrayana* trees) at point of maximum grain spirality. (*) None of the 36 *murrayana* trees sampled had maximum grain spirality at 40, 60, or 90 percent of tree height.

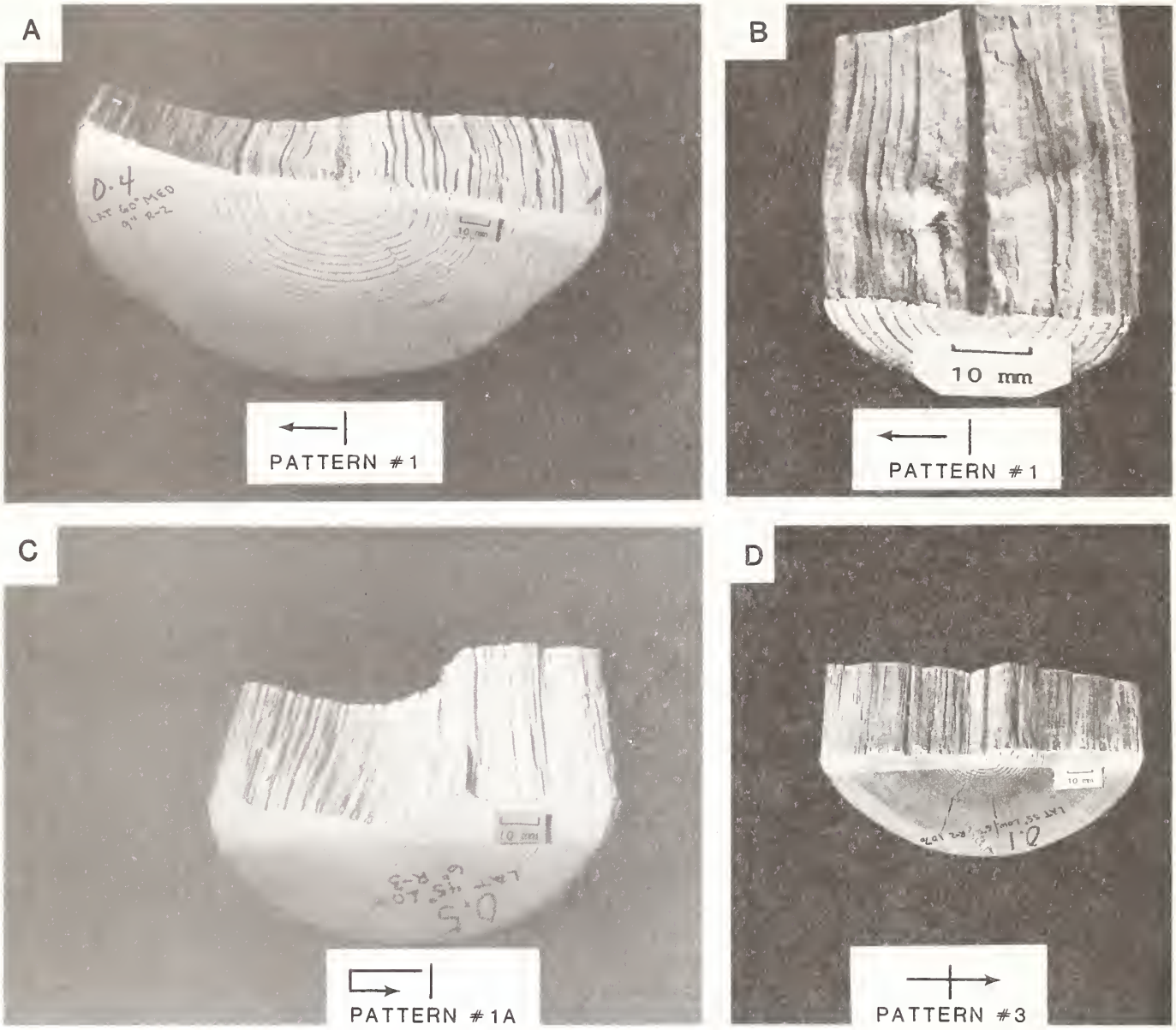



**Figure 11**—Some major patterns of spiral grain in lodgepole pine using numeration from Figure 8. Scale marks show 10 mm. (A) Pattern 1—Left increase away from zero. Stem section showing 105 annual rings at 40 percent of height in tree 228 mm in d.b.h. (B) Pattern 1—Left increase away from zero typical of uppermost stem sections. (C) Pattern 1A—Left increase then decrease toward zero. Stem section showing 35 annual rings at 50 percent of height in tree 152 mm in d.b.h. (D) Pattern 3—Change from left to right spirality typical of aged trees. Stem section shows 133 annual rings at 10 percent of height in tree 152 mm in d.b.h.

Table 10—Percentages of the 10 disks in each tree displaying the various patterns defined in figure 8, by tree d.b.h. and variety

| Pattern | D.b.h. class, mm 76 | 152 | 228 | Average |
|---|---|---|---|---|
| | - - - - - - - - *Percent of disks per tree* - - - - - - - - | | | |
| ***Latifolia* (81 trees of each d.b.h. class; *n* = 243)** | | | | |
| 1 | 22.5 | 14.3 | 14.5 | 17.1 |
| 1A | 28.0 | 26.2 | 23.5 | 25.9 |
| 2 | 3.5 | 4.9 | 6.2 | 4.9 |
| 2A | 3.8 | 7.7 | 7.6 | 6.4 |
| 3 | 32.6 | 38.0 | 35.7 | 35.4 |
| 4 | 1.6 | 1.1 | 1.2 | 1.3 |
| 5 | 3.1 | 2.5 | 3.7 | 3.1 |
| 5A | .9 | 1.7 | 2.0 | 1.5 |
| 6 | .1 | 0 | .4 | .2 |
| 6A | 1.6 | 1.1 | 2.0 | 1.6 |
| 7 | 2.1 | 2.1 | 3.1 | 2.4 |
| 8 | .1 | .1 | .1 | .1 |
| 9 | .1 | .3 | 0 | .1 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 |
| ***Murrayana* (12 trees of each d.b.h. class; *n* = 36)** | | | | |
| 1 | 34.2 | 17.5 | 16.7 | 22.8 |
| 1A | 18.3 | 28.3 | 35.8 | 27.5 |
| 2 | 1.7 | 3.3 | 5.8 | 3.6 |
| 2A | 2.5 | 6.7 | 6.7 | 5.3 |
| 3 | 30.8 | 34.2 | 30.8 | 31.9 |
| 4 | 0 | 0 | 0 | 0 |
| 5 | 5.8 | .8 | 1.7 | 2.8 |
| 5A | 2.5 | 2.5 | .8 | 1.9 |
| 6 | 0 | .8 | 0 | .3 |
| 6A | 0.0 | 1.7 | .8 | .8 |
| 7 | 4.2 | 4.2 | .9 | 3.1 |
| 8 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 |

see table 10. With all data pooled except elevational zone, pattern 1 was significantly more prevalent in low elevational zones than in medium or high zones, as follows:

| Elevational zone | Prevalence of pattern 1 *Percent of disks/tree* |
|---|---|
| Low | 20.7 |
| Medium | 15.2 |
| High | 15.4 |

Also, prevalence of pattern 1 was generally greater in southern latitudes than in northern (except for 57.5 degrees), as follows:

| Latitude *Degrees* | Prevalence of pattern 1 *Percent of disks/tree* |
|---|---|
| 40 | 23.7 |
| 42.5 | 25.2 |
| 45 | 19.3 |
| 47.5 | 14.4 |
| 50 | 15.9 |
| 52.5 | 13.3 |
| 55 | 10.0 |
| 57.5 | 21.4 |
| 60 | 10.8 |

**Pattern #1A—*Latifolia*—**Both patterns 1 and 1A show only left-hand spiral grain, but in pattern 1A the degree of spirality reaches a maximum away from the pith and then decreases toward the bark. With data from all 243 trees pooled, 25.9 percent of the disks in each tree displayed pattern 1A, with standard deviation of 17.4 percent, and range from 0 to 80 percent of the disks in each tree. Small trees tended to have a higher percentage of pattern 1A disks than larger trees (table 10), summarized as follows:

| Tree d.b.h. *mm* | Prevalence of pattern 1A *Percent of disks/tree* |
|---|---|
| 76 | 28.0 |
| 152 | 26.2 |
| 228 | 23.5 |

At all latitudes (except 40 degrees where the percentage of 1A pattern was positively correlated with d.b.h.) percentage of 1A pattern was greater in trees 76 mm in d.b.h. than in one or the other, or both, of the two larger diameters.

Prevalence of pattern 1A tended to be less in low elevational zones than in medium or high zones, as follows:

| Elevational zone | Prevalence of pattern 1A *Percent of disks/tree* |
|---|---|
| Low | 23.5 |
| Medium | 27.2 |
| High | 27.0 |

Only at latitude 47.5 degrees was the reverse true.

The percentage of pattern 1A was lowest in the most southerly latitude (21.8 percent) and in the most northerly latitude (19.3 percent). In the seven intermediate latitudes percentages were greater—averaging in the range from 25.5 to 31.5.

**Pattern #3—*Latifolia*—**Pattern 3 (fig. 8) was most frequent. Disks displaying pattern 3 have left-hand spirality near the pith, but ultimately change to right-hand spirality with increased age from the pith. With data from all 243 trees pooled, 35.4 percent of the disks in each tree displayed pattern 3, with standard deviation of 24.2 percent and range from 0 to 90 percent of the disks in each tree.

The percentage did not vary significantly with d.b.h. class.

With all data pooled except elevational zone, prevalence of pattern 3 tended to be least in low elevational zones as follows:

| Elevational zone | Prevalence of pattern 3 |
|---|---|
| | *Percent of disks/tree* |
| Low | 31.8 |
| Medium | 36.9 |
| High | 37.5 |

This trend was not uniformly true for all latitudes, but for all nine latitudes sampled pattern 3 was more prevalent in low elevational zones than in one or the other, or both, of the two higher zones.

There was a weak trend for increasing prevalence of pattern 3 with increasing latitude; latitude 57.5 did not conform to this trend, however, as follows:

| | Elevational zone | | | |
|---|---|---|---|---|
| Latitude | Low | Medium | High | All trees |
| *Degrees* | *Percent of disks/tree* | | | |
| 40 | 14.4 | 30.0 | 25.6 | 23.3 |
| 42.5 | 25.6 | 40.0 | 22.2 | 29.3 |
| 45 | 34.4 | 36.7 | 25.6 | 32.2 |
| 47.5 | 30.0 | 43.3 | 45.6 | 39.6 |
| 50 | 32.2 | 23.3 | 50.0 | 35.2 |
| 52.5 | 32.2 | 50.0 | 26.7 | 36.3 |
| 55 | 37.8 | 40.0 | 54.4 | 44.1 |
| 57.5 | 21.1 | 38.9 | 28.9 | 29.6 |
| 60 | 58.9 | 30.0 | 58.9 | 49.3 |

**Pattern Frequency Related to Crown Class**—As noted previously, Wellner and Lowery (1967), in a study of western larch stems displaying severe spiral grain, found a close correlation between crown ratio and the ratio of trees having left-hand spiral to those having right-hand spiral at stem surface (fig. 7). The lodgepole pine stems analyzed in the present study did not display such a pronounced curvilinear relationship. With all 243 *latifolia* trees considered, the ratio for each tree of the number of disks displaying left-hand patterns (1, 1A, 2, 2A, 4, and 11) to the number of disks displaying right-hand patterns (3, 5, 5A, 6, 6A, and 8) was plotted against crown ratio for each tree; this plot showed no significant correlation. When the average left/right ratios were computed for each crown ratio with outliers deleted, and these average ratios plotted on the ordinate—a weak positive linear relationship for the 65 data points was observable, as follows:

$Y = 2.068 + 1.386X$

$r = 0.164$; standard error of the estimate = 1.78

where

$Y$ = average of:

$$\frac{\text{Disks per tree with left-hand patterns}}{\text{Disks per tree with right-hand patterns}}$$

$X$ = crown ratio

***Murrayana* vs. *Latifolia***—When entire varietal populations sampled were compared there were no significant differences in average percentages of the three dominant patterns, as follows (standard deviations shown in parentheses):

| Pattern | 243 *latifolia* trees | 36 *murrayana* trees |
|---|---|---|
| | *Percent of disks/tree* | |
| 1 | 17.1 (15.6) | 22.8 (19.8) |
| 1A | 25.9 (17.4) | 27.5 (17.8) |
| 3 | 35.4 (24.2) | 31.9 (22.4) |

## Volume-Weighted Tree-Average Growth Ring Width in Stemwood

***Latifolia***—In the *latifolia* trees sampled, volume-weighted tree-average growth ring width averaged 1.11 mm, with standard deviation of 0.6 mm and range from 0.2 to 3.2 mm (table 11). This wide variability in average growth ring width reflects the prevalence of trees that stagnate at an early age in natural unthinned stands (fig. 12) and the infrequent occurrence of mature trees that have sustained uniform rapid growth from pith to cambium (fig. 13). Our observations suggest, however, that with appropriate management lodgepole pine **can** sustain rapid growth from youth to maturity on many sites in North America.

In the natural *latifolia* stands sampled, average growth ring width varied significantly with each of the three major factors in the study—d.b.h., elevational zone, and latitude (table 11). As previously noted (table 1), the sample trees were selected in such a way that most of the small-diameter trees were suppressed while the larger trees were the fast growers. It came as no surprise, therefore, that average growth ring width was positively correlated ($r = 0.424$) with d.b.h., as follows:

| D.b.h. | Growth ring width |
|---|---|
| *mm* | *mm* |
| 76 | 0.81 |
| 152 | 1.12 |
| 228 | 1.40 |

While not significantly correlated with absolute elevation (m), average growth ring width had a negative relationship with elevational zone, as follows:

| Elevational zone | Growth ring width |
|---|---|
| | *mm* |
| Low | 1.34 |
| Medium | 1.05 |
| High | .94 |

The significant but weak negative correlation with latitude ($r = -0.212$) showed a less clear trend. Trees sampled in the southernmost (40 degrees) and the northernmost (60 degrees) latitudes had average growth ring width of 0.96 and 0.69 mm, respectively,

**Table 11**—Mean, standard deviation, and range of volume-weighted tree-average growth ring width in stemwood of *latifolia*, by latitude, elevational zone, and tree d.b.h.[1]

| Elevation | Tree d.b.h. 76 mm | 152 mm | 228 mm | All trees |
|---|---|---|---|---|
| | | *mm* | | |
| | **40 degrees latitude** | | | |
| Low | 0.63(0.2) | 1.09(0.2) | 1.38(0.2) | 1.04(0.4) |
| | 0.4-0.9 | 0.9-1.4 | 1.2-1.6 | 0.4-1.6 |
| Medium | 0.53(0.1) | 1.19(0.2) | 1.34(0.2) | 1.02(0.4) |
| | 0.4-0.7 | 1.0-1.4 | 1.1-1.6 | 0.4-1.6 |
| High | 0.59(0.2) | 0.97(0.4) | 0.89(0.4) | 0.82(0.3) |
| | 0.4-0.9 | 0.6-1.3 | 0.6-1.3 | 0.4-1.3 |
| | **42.5 degrees latitude** | | | |
| Low | 1.25(0.6) | 1.51(0.7) | 2.49(0.8) | 1.75(0.8) |
| | 0.6-1.8 | 1.0-2.3 | 1.6-3.1 | 0.6-3.1 |
| Medium | 0.81(0.3) | 1.30(0.9) | 1.56(0.6) | 1.22(0.7) |
| | 0.5-1.0 | 0.6-2.3 | 0.9-2.2 | 0.5-2.3 |
| High | 1.18(0.3) | 1.42(0.9) | 1.33(0.7) | 1.31(0.6) |
| | 0.8-1.4 | 0.7-2.4 | 0.6-2.0 | 0.6-2.4 |
| | **45 degrees latitude** | | | |
| Low | 1.09(0.4) | 1.68(0.5) | 1.77(0.1) | 1.51(0.5) |
| | 0.8-1.5 | 1.4-2.3 | 1.7-1.9 | 0.8-2.3 |
| Medium | 0.82(0.3) | 1.41(0.4) | 1.17(0.7) | 1.13(0.5) |
| | 0.5-1.1 | 1.0-1.8 | 0.6-1.9 | 0.5-1.9 |
| High | 0.94(0.3) | 1.36(0.3) | 1.60(0.5) | 1.30(0.4) |
| | 0.8-1.2 | 1.1-1.7 | 1.1-2.0 | 0.8-2.0 |
| | **47.5 degrees latitude** | | | |
| Low | 1.86(1.2) | 1.30(0.5) | 1.98(0.7) | 1.71(0.8) |
| | 0.8-3.2 | 0.8-1.7 | 1.2-2.6 | 0.8-3.2 |
| Medium | 1.98(0.8) | 0.77(0.2) | 1.18(0.3) | 1.31(0.7) |
| | 1.1-2.5 | 0.7-1.0 | 1.0-1.4 | 0.7-2.5 |
| High | 0.56(0.3) | 1.10(0.6) | 1.50(0.8) | 1.05(0.7) |
| | 0.2-0.9 | 0.4-1.7 | 0.7-2.3 | 0.2-2.3 |
| | **50 degrees latitude** | | | |
| Low | 0.92(0.4) | 1.57(0.5) | 1.89(0.5) | 1.46(0.6) |
| | 0.6-1.3 | 1.0-2.0 | 1.4-2.2 | 0.6-2.2 |
| Medium | 0.81(0.3) | 0.92(0.3) | 1.15(0.4) | 0.96(0.3) |
| | 0.5-1.0 | 0.6-1.1 | 0.7-1.5 | 0.5-1.5 |
| High | 0.44(0.1) | 0.75(0.05) | 1.03(0.05) | 0.74(0.3) |
| | 0.4-0.5 | 0.7-0.8 | 1.0-1.1 | 0.4-1.1 |
| | **52.5 degrees latitude** | | | |
| Low | 0.78(0.3) | 1.49(0.7) | 1.65(0.4) | 1.30(0.6) |
| | 0.5-1.1 | 1.1-2.3 | 1.3-2.1 | 0.5-2.3 |
| Medium | 0.68(0.3) | 0.97(0.5) | 1.15(0.3) | 0.93(0.4) |
| | 0.4-0.8 | 0.6-1.5 | 0.9-1.5 | 0.4-1.5 |
| High | 0.54(0.3) | 0.91(0.2) | 1.10(0.1) | 0.85(0.3) |
| | 0.4-0.8 | 0.8-1.1 | 1.0-1.2 | 0.4-1.2 |
| | **55 degrees latitude** | | | |
| Low | 0.69(0.4) | 0.81(0.5) | 1.13(0.6) | 0.87(0.5) |
| | 0.3-1.1 | 0.5-1.3 | 0.8-1.8 | 0.3-1.8 |
| Medium | 0.94(0.5) | 1.08(0.2) | 1.65(0.3) | 1.23(0.4) |
| | 0.5-1.4 | 0.9-1.3 | 1.4-1.9 | 0.5-1.9 |
| High | 0.74(0.4) | 0.92(0.03) | 1.32(0.2) | 1.00(0.3) |
| | 0.5-1.2 | 0.9-1.0 | 1.2-1.5 | 0.5-1.5 |
| | **57.5 degrees latitude** | | | |
| Low | 0.82(0.1) | 1.63(0.1) | 2.53(0.1) | 1.66(0.7) |
| | 0.7-0.9 | 1.5-1.7 | 2.4-2.7 | 0.7-2.7 |
| Medium | 0.52(0.3) | 1.09(0.8) | 0.92(0.1) | 0.85(0.5) |
| | 0.3-0.9 | 0.6-2.0 | 0.9-1.0 | 0.3-2.0 |
| High | 0.50(0.1) | 0.85(0.2) | 1.30(0.3) | 0.88(0.4) |
| | 0.4-0.6 | 0.6-1.1 | 1.0-1.6 | 0.4-1.6 |
| | **60 degrees latitude** | | | |
| Low | 0.44(0.1) | 0.87(0.04) | 1.04(0.2) | 0.78(0.3) |
| | 0.4-0.5 | 0.8-0.9 | 0.8-1.3 | 0.4-1.3 |
| Medium | 0.45(0.1) | 0.81(0.2) | 1.11(0.5) | 0.79(0.4) |
| | 0.3-0.5 | 0.5-1.0 | 0.8-1.7 | 0.3-1.7 |
| High | 0.27(0.1) | 0.52(0.1) | 0.72(0.1) | 0.50(0.2) |
| | 0.2-0.3 | 0.4-0.6 | 0.6-0.9 | 0.2-0.9 |
| Pooled | 0.81(0.5) | 1.12(0.5) | 1.40(0.6) | 1.11(0.6) |
| | 0.2-3.2 | 0.4-2.4 | 0.6-3.1 | 0.2-3.2 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 243, that is, 27 per latitude.

**Figure 12**—Most of the lodgepole pines studied showed good radial growth in early years but virtual cessation of radial growth in later years as stands stagnated. This *latifolia* section (taken at 10 percent of stem height from a medium-elevation tree 152 mm in d.b.h.) displays 115 annual rings; growth slowed drastically after the 28th year.

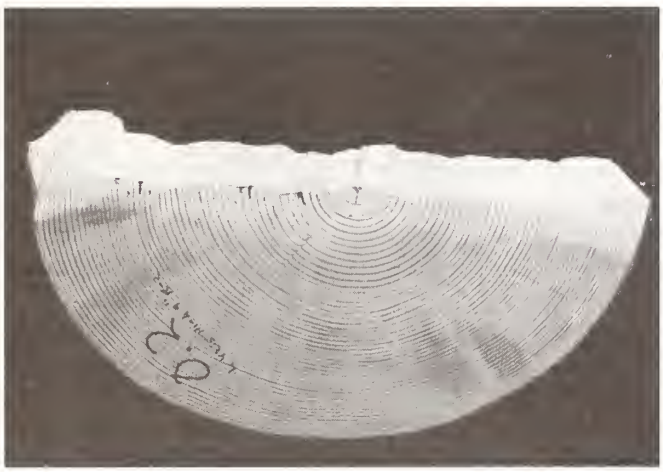


**Figure 13**—Mature trees infrequently displayed sustained radial growth rate from pith to cambium. This *latifolia* section (taken at 20 percent of stem height from a high-elevation tree 228 mm in d.b.h. growing at 42.5 degrees latitude) has pith well centered, little spiral grain, and displays 66 such uniform annual rings. The section is 197 mm in diameter; average ring width is 1.5 mm.

while in three of the southerly latitudes—42.5, 45, and 47.5 degrees—growth rings averaged much wider (1.37 mm) and those in the more northern latitudes of 50, 52.5, 55, and 57.5 degrees averaged intermediate in width (1.06 mm) as follows:

| Latitude | Volume-weighted tree-average growth ring width |
|---|---|
| *Degrees* | *mm* |
| 40 | 0.96 |
| 42.5 | 1.43 |
| 45 | 1.31 |
| 47.5 | 1.36 |
| 50 | 1.05 |
| 52.5 | 1.03 |
| 55 | 1.03 |
| 57.5 | 1.13 |
| 60 | .69 |

**Correlations**—In addition to the correlation with latitude, elevational zone, and d.b.h., volume-weighted tree-average growth ring width in *latifolia* was correlated with many tree characteristics, as follows:

| Characteristic | Positive *r* | Negative *r* |
|---|---|---|
| Average ring width at 152-mm stump height | 0.901 | |
| Tree age at 152-mm stump height | | –0.564 |
| Length of live crown | .539 | |
| Stemwood diameter at base of live crown | .524 | |
| Sapwood weight in stem | .495 | |
| Foliage weight, ovendry | .480 | |
| Taproot length | .469 | |
| Number of live branches | .437 | |
| Width of live crown | .432 | |
| Stemwood diameter at 152-mm stump height | .425 | |
| D.b.h. | .424 | |
| Average live branch angle to stem above branch | | –.420 |
| Live branch weight, ovendry | .419 | |
| Branchwood percent of complete-tree ovendry weight | .417 | |
| Stemwood taper to base of live crown, millimeters/meter | .411 | |
| Dead branch weight, ovendry | .404 | |
| Stemwood moisture content, percent of ovendry weight | .401 | |
| Complete-tree weight, ovendry | .400 | |
| Total stump-root weight with bark, ovendry | .394 | |
| Stemwood specific gravity | | –.388 |
| Crown ratio | .387 | |
| Complete-tree moisture content, percent of ovendry weight | .387 | |
| Sapwood moisture content, percent of ovendry weight | .375 | |
| Total stemwood weight, ovendry | .365 | |

| Characteristic | Positive *r* | Negative *r* |
|---|---|---|
| Total stem weight with bark, ovendry | .364 | |
| Stem bark thickness at 152-mm stump height | .318 | |
| Tree height to apical tip | .311 | |
| Total-bark percent of complete-tree ovendry weight | | –.291 |
| Stembark specific gravity | | –.269 |
| Stump-average bark thickness | .259 | |
| Branch bark thickness | .255 | |
| Average live branch diameter | .248 | |
| Latitude, degrees | | –.212 |
| Foliage percent of complete-tree ovendry weight | .206 | |
| Percent of right-handedness of maximum spirality | | –.200 |
| Stemwood percent of complete-tree ovendry weight | | –.162 |
| Longitude, degrees | | –.152 |
| Rootwood percent of complete-tree ovendry weight | | –.145 |
| Total number of cones on the first foot of the top 25 branches | .143 | |
| Tree-average pith eccentricity in stem, millimeters | .141 | |

It has been noted that rapid radial growth of *latifolia* is favored by low elevational zone and midlatitudes. In additional summary of *latifolia* trees, greatest growth ring width (volume-weighted tree-average) will be found in young trees rather than old. Ring widths are greatest in trees with high crown ratios, long, wide crowns bearing many cones on the top 25 branches, and much foliage, with a large percentage of complete-tree ovendry weight represented by foliage and branches. Many heavy, thick-barked, large-diameter branches making a small angle with the stem above each branch are associated with wide growth rings.

Wide growth rings are also associated with trees having long taproots, heavy stump-root systems, and stumps with thick bark.

Stems of trees with wide rings tend to have a large diameter at the stump, at breast height, and at the base of the live crown. Wide rings are associated with heavy stems having much sapwood of high moisture content, much taper below the live crown, and low specific gravity (both wood and bark). Ring width also has a positive correlation with stem-average moisture content and weak positive correlation with stem-average pith eccentricity. Stems with a high percentage of left-hand maximum spirality have wider rings than those with predominantly right-hand maximum spirals.

All diameters considered, rings are wider in tall trees than in short. This generalization is not true, however, if d.b.h. classes are considered separately—that is, tall trees of a particular diameter class do not have wider growth rings than short trees of the same diameter class.

It is of interest that volume-weighted tree-average growth ring width is not significantly correlated with heartwood weight, stemwood-average percentage of compression wood, or stemwood-average fiber length.

***Murrayana* vs. *Latifolia*—Annual Growth Increment**—In entire populations sampled (tables 11 and 12), volume-weighted tree-average annual growth ring width was significantly greater in variety *murrayana* (1.40 mm, standard deviation 0.67) than in *latifolia* (1.11 mm, standard deviation 0.57).

**Table 12**—Mean, standard deviation, and range of volume-weighted tree-average growth ring width in stemwood of *murrayana*, by latitude and tree d.b.h.[1]

| Latitude | Tree d.b.h 76 mm | 152 mm | 228 mm | All trees |
|---|---|---|---|---|
| *Degrees* | *Degrees* | | | |
| 37.5 | 1.01(0.3) | 1.47(0.4) | 2.13(0.3) | 1.54(0.6) |
| | 0.7-1.3 | 1.1-1.8 | 2.0-2.5 | 0.7-2.5 |
| 40 | 1.02(0.5) | 1.72(0.6) | 1.90(0.05) | 1.55(0.6) |
| | 0.7-1.6 | 1.2-2.4 | 1.85-1.94 | 0.7-2.4 |
| 42.5 | 0.82(0.3) | 0.74(0.1) | 1.04(0.05) | 0.87(0.2) |
| | 0.5-1.1 | 0.6-0.9 | 1.01-1.10 | 0.5-1.1 |
| 45 | 0.87(0.4) | 1.72(0.8) | 2.37(0.9) | 1.65(0.9) |
| | 0.4-1.1 | 0.8-2.4 | 1.3-3.0 | 0.4-3.0 |
| Pooled | 0.93(0.3) | 1.41(0.6) | 1.86(0.7) | 1.40(0.7) |
| | 0.4-1.6 | 0.6-2.4 | 1.0-3.0 | 0.4-3.0 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total number of trees in the sample = 36, that is, 9 per latitude.

As with *latifolia*, means were positively correlated with d.b.h. in *murrayana* as follows:

| D.b.h. | *Latifolia* (81 trees/d.b.h.) | *Murrayana* (12 trees/d.b.h.) |
|---|---|---|
| *mm* | *Ring width, mm* | |
| 76 | 0.81 | 0.93 |
| 152 | 1.12 | 1.41 |
| 228 | 1.40 | 1.86 |

While means differed significantly with latitude, trends were different in *latifolia* than in *murrayana* at medium elevation, as follows:

| Latitude | *Latifolia* | *Murrayana* |
|---|---|---|
| *Degrees* | *mm* | |
| 37.5 | — | 1.54 |
| 40 | 1.02 | 1.55 |
| 42.5 | 1.22 | .87 |
| 45 | 1.13 | 1.65 |

As noted previously, in all the stands sampled the smaller-diameter trees tended to be suppressed by competition (fig. 12). Ages at 152-mm-high stump top averaged greater for *latifolia* than for *murrayana* (table 1), as follows:

| D.b.h. | *Latifolia* | *Murrayana* |
|---|---|---|
| *mm* | *Years* | |
| 76 | 73 | 63 |
| 152 | 92 | 82 |
| 228 | 104 | 86 |

And *latifolia* trees averaged taller from 152-mm-high stump top to apical tip than *murrayana* (table 1), as follows:

| D.b.h. | *Latifolia* | *Murrayana* |
|---|---|---|
| *mm* | *Meters* | |
| 76 | 9.3 | 7.4 |
| 152 | 15.6 | 13.7 |
| 228 | 19.1 | 18.7 |

As a result of this height differential, *latifolia* trees (stump to apical tip) had more stemwood volume and weight ovendry (Koch 1987)—but took more years to achieve this volume and weight—than *murrayana* of the same d.b.h., as follows:

| D.b.h. | *Latifolia* | *Murrayana* |
|---|---|---|
| *mm* | *Volume, thousand $cm^3$* | |
| 76 | 21.2 | 15.8 |
| 152 | 140.3 | 111.1 |
| 228 | 377.4 | 336.1 |

| D.b.h. | *Latifolia* | *Murrayana* |
|---|---|---|
| *mm* | *Ovendry weight, kg* | |
| 76 | 9.14 | 7.63 |
| 152 | 59.13 | 49.46 |
| 228 | 154.08 | 137.55 |

From the foregoing tabulations, annual increments of stemwood volume and ovendry weight can be calculated, as follows:

| D.b.h. | *Latifolia* | *Murrayana* |
|---|---|---|
| *mm* | *Thousand $cm^3$/year* | |
| 76 | 0.29 | 0.25 |
| 152 | 1.53 | 1.35 |
| 228 | 3.63 | 3.91 |

| D.b.h. | *Latifolia* | *Murrayana* |
|---|---|---|
| *mm* | *kg/year* | |
| 76 | 0.13 | 0.12 |
| 152 | .64 | .60 |
| 228 | 1.48 | 1.60 |

It appears, therefore, that with all tree data pooled *latifolia* 76 mm and 152 mm in d.b.h. slightly outgrew *murrayana* in stemwood annual increments of both volume and ovendry weight—but in trees 228 mm in d.b.h., *murrayana* slightly outgrew *latifolia*.

## RESULTS (WITHIN-TREE VARIATION)

This portion of the Results section is concerned with variations within trees. Previously described within-tree variations in gross external stem characteristics of these lodgepole pine trees include taper (Koch 1987) and stem out-of-roundness (Koch and others 1990). Internal characteristics previously described include pith eccentricity (Koch and others 1990), and compression wood content (Koch and others 1990).

Following are results from the present study related to within-tree variations in spiral grain:

- Patterns of spirality related to height in tree
- Maximum spirality in each section related to height and radial position
- Direction of spirality related to distance from pith and height in tree
- Direction and degree of spirality related to radius selected (long or short)
- Spirality correlated with ring width, and age and distance from pith
- Disk properties correlated with disk maximum spirality.

Results related to within-tree variations in the spatial arrangement and dimensions of annual growth rings are also presented:

- Disk-average ring width related to height in tree
- Ring width related to radius and height at which sampled
- Ring age related to radius and height at which sampled
- Tree height growth
- Estimate of tree height based on stump diameter and age.

## Patterns of Spirality Related to Height in Tree

As noted previously, in all diameter classes and in both varieties spirality patterns 1, 1A, and 3 dominate (tables 13 and 14). The proportions of these three major patterns differ significantly with height in tree for each diameter class (see table 1 for average tree heights). In *latifolia*, prevalence of pattern 1 (left-hand spirality with degree increasing with increasing distance from pith) is low in lower stem sections, but increases rapidly in upper sections (fig. 14 and table 13). Incidence of pattern 1A (also left hand but first increasing in degree and then decreasing with increased distance from pith) is least in the lower stem, increases to a maximum near 70 percent of tree height, and then decreases somewhat in uppermost stem sections. Prevalence of pattern 3

**Table 13**—Variations in prevalence of the 13 patterns of spirality (defined in fig. 8) with height in *latifolia* trees of three diameters—data from the nine latitudes and three elevational zones pooled. At each height, values sum to 100 percent (plus or minus rounding errors) based on data from 81 trees

| Pattern | Height in tree from stump top to apical tip (percent) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| | *Percent* | | | | | | | | | |
| | **76 mm d.b.h.** | | | | | | | | | |
| 1 | 17.3 | 9.9 | 3.7 | 3.7 | 8.6 | 9.9 | 8.6 | 29.6 | 56.8 | 76.5 |
| 1A | 6.2 | 21.0 | 22.2 | 34.6 | 29.6 | 39.5 | 44.4 | 42.0 | 25.9 | 14.8 |
| 2 | 3.7 | 2.5 | 7.4 | 3.7 | 6.2 | 4.9 | 4.9 | 1.2 | 0 | 0 |
| 2A | 6.2 | 4.9 | 3.7 | 7.4 | 4.9 | 3.7 | 3.7 | 0 | 2.5 | 1.2 |
| 3 | 40.7 | 54.3 | 51.9 | 42.0 | 43.2 | 37.0 | 25.9 | 21.0 | 9.9 | 0 |
| 4 | 1.2 | 0 | 2.5 | 1.2 | 1.2 | 1.2 | 3.7 | 2.5 | 1.2 | 1.2 |
| 5 | 13.6 | 2.5 | 6.2 | 1.2 | 2.5 | 0 | 1.2 | 0 | 1.2 | 2.5 |
| 5A | 6.2 | 0 | 0 | 0 | 0 | 1.2 | 1.2 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 |
| 6A | 0 | 4.9 | 1.2 | 1.2 | 2.5 | 1.2 | 2.5 | 1.2 | 0 | 1.2 |
| 7 | 4.9 | 0 | 1.2 | 3.7 | 1.2 | 1.2 | 3.7 | 2.5 | 1.2 | 1.2 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0 |
| 9 | 0 | 0 | 0 | 1.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **152 mm d.b.h.** | | | | | | | | | |
| 1 | 17.3 | 6.2 | 3.7 | 3.7 | 3.7 | 3.7 | 8.6 | 16.0 | 24.7 | 55.6 |
| 1A | 9.9 | 18.5 | 13.6 | 24.7 | 23.5 | 34.6 | 34.6 | 42.0 | 38.3 | 22.2 |
| 2 | 2.5 | 6.2 | 7.4 | 6.2 | 3.7 | 3.7 | 4.9 | 3.7 | 8.6 | 2.5 |
| 2A | 12.3 | 16.0 | 6.2 | 8.6 | 9.9 | 6.2 | 7.4 | 3.7 | 4.9 | 1.2 |
| 3 | 32.1 | 45.7 | 61.7 | 50.6 | 49.4 | 49.4 | 35.8 | 28.4 | 17.3 | 9.9 |
| 4 | 0 | 0 | 1.2 | 1.2 | 2.5 | 0 | 0 | 3.7 | 2.5 | 0 |
| 5 | 11.1 | 4.9 | 1.2 | 1.2 | 2.5 | 1.2 | 1.2 | 0 | 0 | 1.2 |
| 5A | 8.6 | 0 | 3.7 | 1.2 | 1.2 | 1.2 | 0 | 0 | 1.2 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6A | 3.7 | 0 | 0 | 0 | 1.2 | 0 | 2.5 | 1.2 | 2.5 | 0 |
| 7 | 2.5 | 2.5 | 1.2 | 2.5 | 2.5 | 0 | 3.7 | 1.2 | 0 | 4.9 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0 | 0 | 1.2 |
| | **228 mm d.b.h.** | | | | | | | | | |
| 1 | 11.1 | 9.9 | 8.6 | 6.2 | 8.6 | 6.2 | 18.5 | 7.4 | 22.2 | 46.9 |
| 1A | 16.0 | 4.9 | 25.9 | 19.8 | 18.5 | 22.2 | 23.5 | 37.0 | 37.0 | 29.6 |
| 2 | 2.5 | 7.4 | 2.5 | 6.2 | 12.3 | 12.3 | 3.7 | 8.6 | 4.9 | 1.2 |
| 2A | 8.6 | 11.1 | 9.9 | 13.6 | 7.4 | 6.2 | 6.2 | 4.9 | 4.9 | 3.7 |
| 3 | 29.6 | 45.7 | 43.2 | 44.4 | 43.2 | 44.4 | 38.3 | 34.6 | 24.7 | 8.6 |
| 4 | 2.5 | 2.5 | 2.5 | 1.2 | 0 | 0 | 0 | 1.2 | 1.2 | 1.2 |
| 5 | 7.4 | 7.4 | 3.7 | 2.5 | 1.2 | 4.9 | 1.2 | 2.5 | 3.7 | 2.5 |
| 5A | 8.6 | 3.7 | 1.2 | 0 | 1.2 | 1.2 | 0 | 0 | 1.2 | 2.5 |
| 6 | 0 | 0 | 1.2 | 1.2 | 1.2 | 0 | 0 | 0 | 0 | 0 |
| 6A | 3.7 | 3.7 | 0 | 2.5 | 2.5 | 1.2 | 2.5 | 2.5 | 0 | 1.2 |
| 7 | 9.9 | 3.7 | 1.2 | 2.5 | 3.7 | 1.2 | 4.9 | 1.2 | 0 | 2.5 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 14—Variations in prevalence of the 13 patterns of spirality (defined in fig. 8) with height in *murrayana* trees of three diameters—data from the four latitudes pooled. At each height, values sum to 100 percent (plus or minus minor rounding errors) based on data from 12 trees

| Pattern | Height in tree from stump top to apical tip (percent) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| | *Percent* | | | | | | | | | |
| | **76 mm d.b.h.** | | | | | | | | | |
| 1 | 8.3 | 8.3 | 16.7 | 16.7 | 25.0 | 16.7 | 33.3 | 66.7 | 66.7 | 83.3 |
| 1A | 8.3 | 8.3 | 16.7 | 25.0 | 25.0 | 33.3 | 16.7 | 16.7 | 25.0 | 8.3 |
| 2 | 0 | 0 | 8.3 | 8.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2A | 0 | 8.3 | 0 | 8.3 | 0 | 0 | 8.3 | 0 | 0 | 0 |
| 3 | 33.3 | 25.0 | 58.3 | 33.3 | 41.7 | 50.0 | 41.7 | 16.7 | 8.3 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 16.7 | 25.0 | 0 | 8.3 | 0 | 0 | 0 | 0 | 0 | 8.3 |
| 5A | 16.7 | 8.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 16.7 | 16.7 | 0 | 0 | 8.3 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **152 mm d.b.h.** | | | | | | | | | |
| 1 | 8.3 | 0 | 16.7 | 0 | 0 | 8.3 | 8.3 | 25.0 | 41.7 | 66.7 |
| 1A | 0 | 25.0 | 16.7 | 25.0 | 33.3 | 16.7 | 58.3 | 41.7 | 41.7 | 25.0 |
| 2 | 8.3 | 0 | 0 | 0 | 0 | 8.3 | 0 | 8.3 | 8.3 | 0 |
| 2A | 16.7 | 0 | 0 | 16.7 | 8.3 | 16.7 | 8.3 | 0 | 0 | 0 |
| 3 | 41.7 | 58.3 | 50.0 | 41.7 | 58.3 | 41.7 | 25.0 | 16.7 | 8.3 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 8.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5A | 8.3 | 8.3 | 0 | 8.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 16.7 | 8.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 8.3 | 8.3 | 0 | 0 | 0 | 8.3 | 0 | 8.3 | 0 | 8.3 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **228 mm d.b.h.** | | | | | | | | | |
| 1 | 50.0 | 8.3 | 8.3 | 0 | 0 | 8.3 | 8.3 | 16.7 | 16.7 | 50.0 |
| 1A | 8.3 | 8.3 | 33.3 | 41.7 | 33.3 | 25.0 | 33.3 | 66.7 | 58.3 | 50.0 |
| 2 | 0 | 16.7 | 0 | 0 | 0 | 25.0 | 8.3 | 0 | 8.3 | 0 |
| 2A | 8.3 | 25.0 | 8.3 | 0 | 8.3 | 8.3 | 0 | 8.3 | 0 | 0 |
| 3 | 33.3 | 41.7 | 50.0 | 41.7 | 58.3 | 25.0 | 41.7 | 8.3 | 8.3 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 16.7 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8.3 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6A | 0 | 0 | 0 | 0 | 0 | 0 | 8.3 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 8.3 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

(changing from left-hand to right-hand spirality with increasing distance from pith) increases from an initially high proportion (30 to 40 percent) at stump height to a maximum near 10 or 20 percent of tree height and then decreases sharply in the upper stem.

Similar variations in prevalence of major spirality patterns with height in tree were also observed in variety *murrayana* (fig. 15 and table 14).

## Maximum Spirality in Each Section Related to Height and Radial Position

As previously noted, a frequency distribution (fig. 10) illustrates not only the varietal differences, but also the wide distribution of the percentage of tree height at which maximum spirality was observed. Maximum spirality most frequently occurred—not at average values—but at 152-mm-high stump top

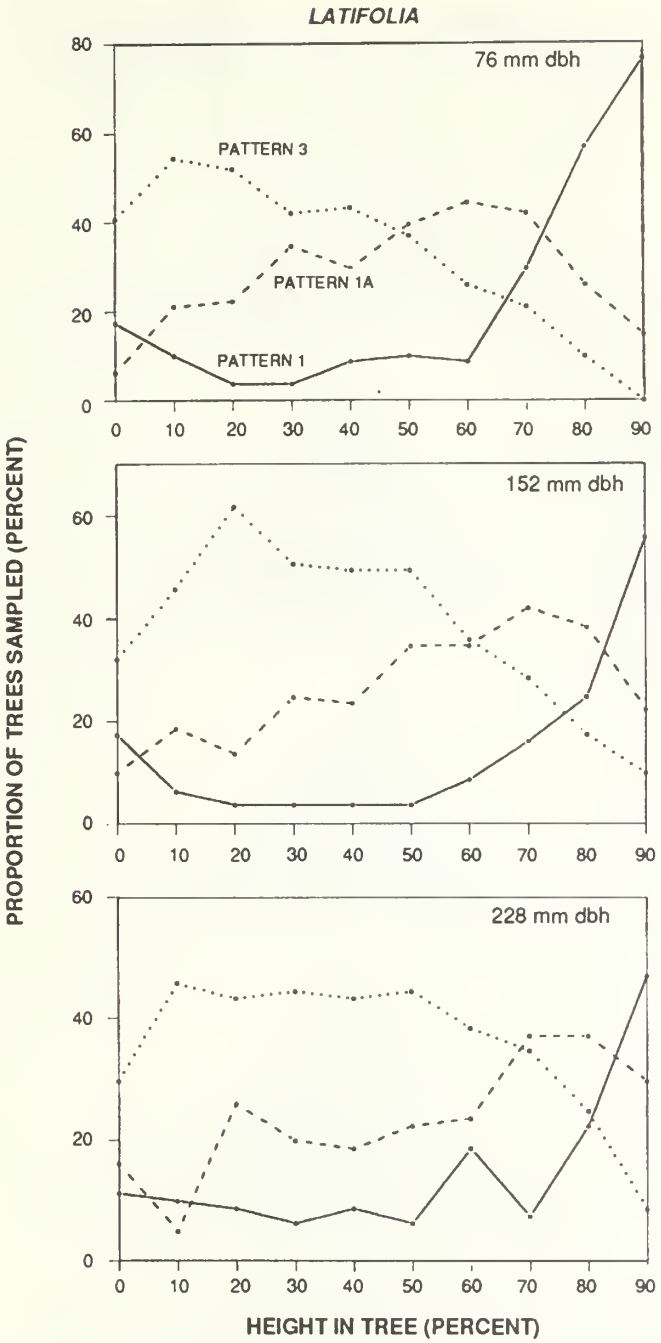



**Figure 14**—Variations in *latifolia* of prevalence of the three major patterns of spirality (see fig. 8 for definitions) with height from 152-mm-high stump top to apical tip in trees of three d.b.h. classes. Each point on each line is defined by data from 81 trees.

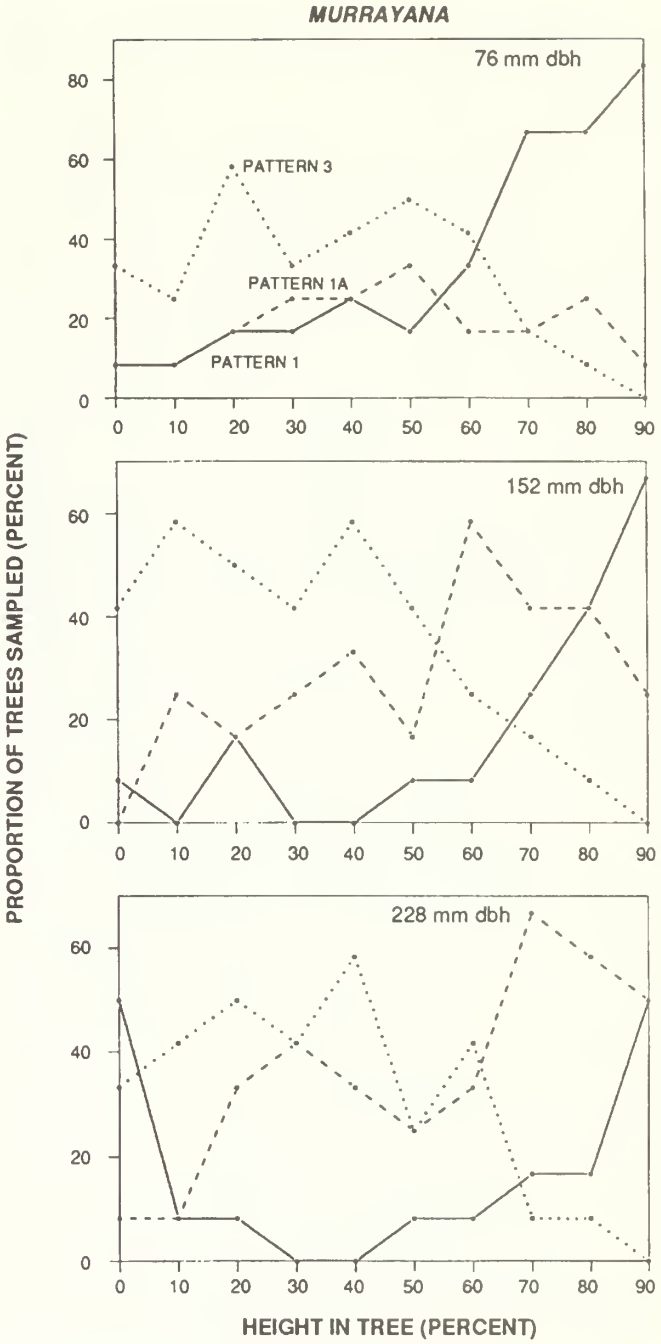



**Figure 15**—Variations in *murrayana* of prevalence of the three major patterns of spirality (see fig. 8 for definitions) with height from 152-mm-high stump top to apical tip in trees of three d.b.h. classes. Each point on each line is defined by data from 12 trees.

for both varieties, with a second and lesser concentration of maximum spirality occurring at 70 percent of tree height in *latifolia* and 80 percent in *murrayana*.

Average angularity of maximum spirality observed at each percentage of tree height differed somewhat between varieties (fig. 16). *Murrayana* spirality was inversely correlated with height—particularly in trees 76 mm and 152 mm in d.b.h.; *latifolia* maximum spirality at 10 percent of tree height and above did not vary greatly with increasing height in tree.

Average angularity of maximum spirality observed at each percentage of tree height (fig. 16) gives no

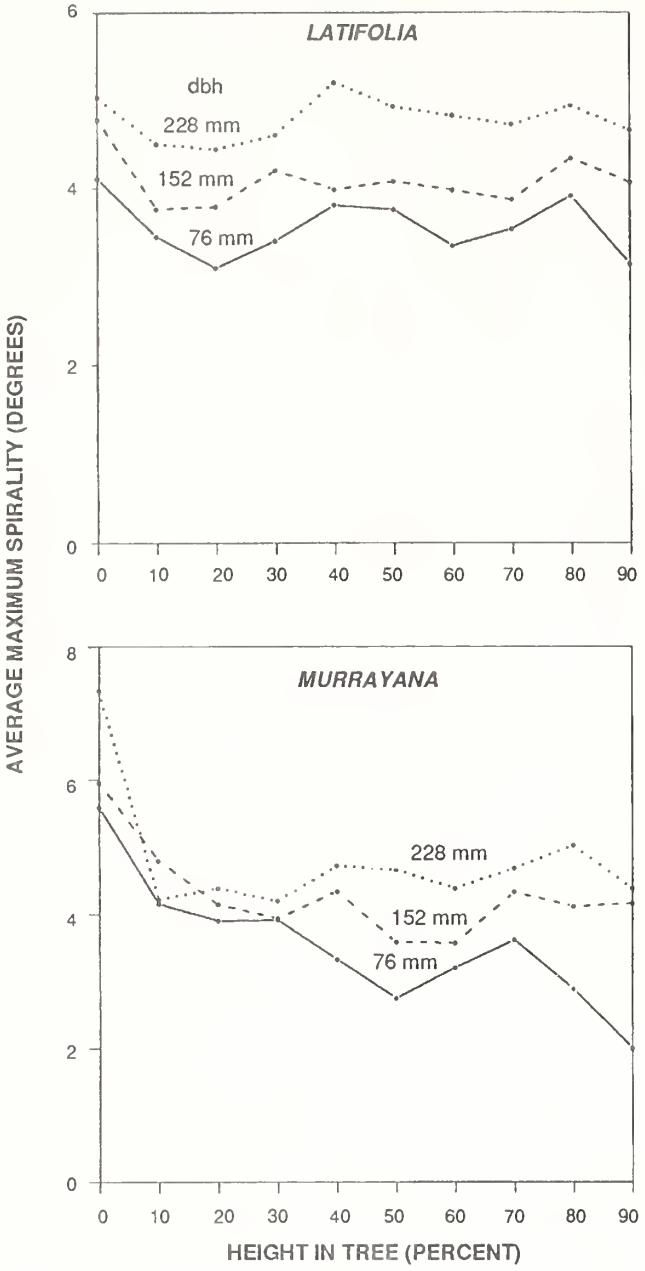



**Figure 16**—Maximum spirality observed in disks sampled at 10 percent height intervals from 152-mm-high stump top to apical tip in trees of two varieties and three diameters at breast height. Each point on each line is the average of data from 81 trees of *latifolia* or 12 trees of *murrayana*.

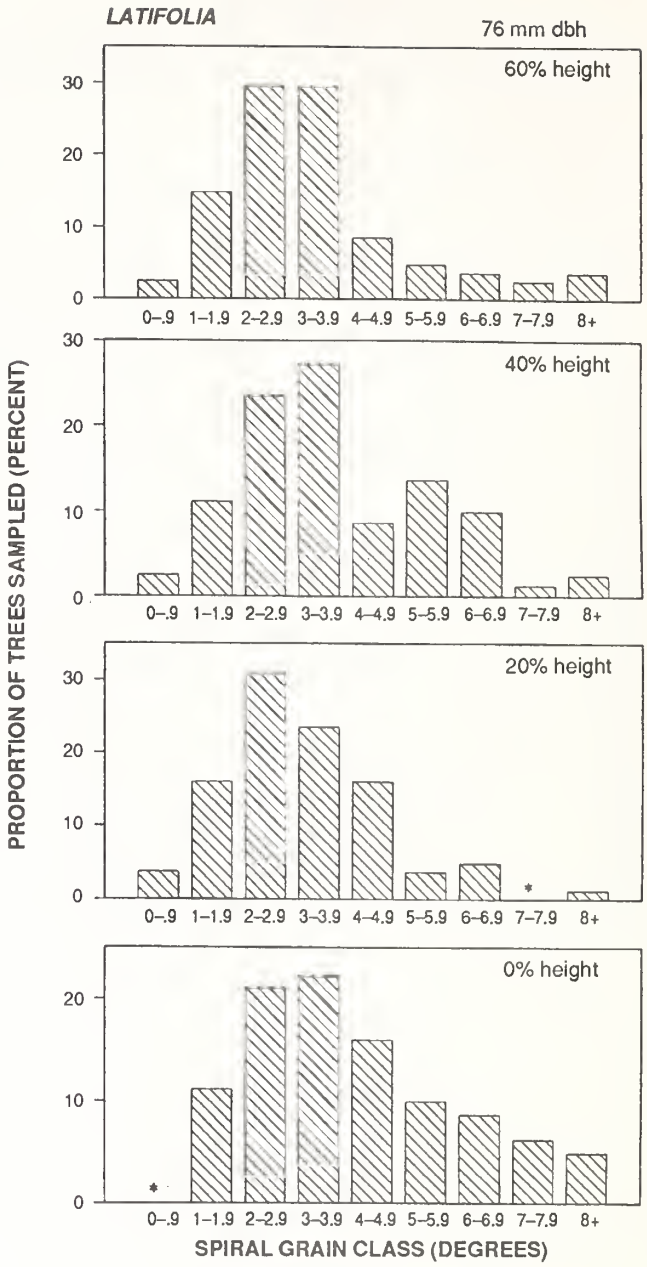



**Figure 17**—Frequency distribution of maximum grain spirality at four heights in *latifolia* trees 76 mm in d.b.h. Each of the four bar charts represents data from 81 trees. An asterisk (*) indicates none of the 81 trees had sections of the spiral grain class indicated.

idea of the variation around this average, however. When such variation in *latifolia* is examined at four heights (0, 20, 40, and 60 percent) it is seen (figs. 17, 18, and 19) that the degree of maximum spirality is more-or-less normally distributed around the means depicted in figure 16, but is somewhat skewed toward low angles in trees 76 mm and 152 mm in d.b.h. In *latifolia* at these heights, from 50 to 70 percent of the sections displayed 2 to 5 degrees maximum spirality and 10 to 20 percent 5 to 6 degrees of maximum spirality. A significant proportion of sections had maximum spirality in excess of 8 degrees—particularly those from larger trees and at stump height (figs. 17, 18, and 19).

The sample size for *murrayana* was insufficient to develop similar distribution charts that would be meaningful.

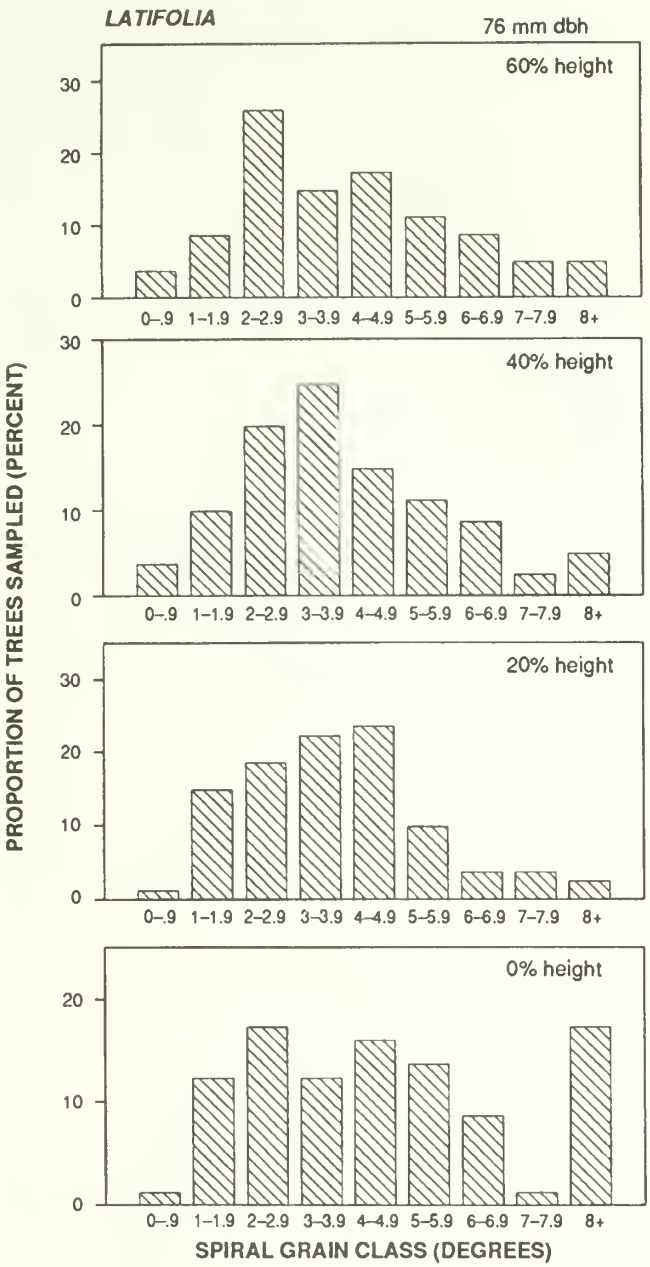



**Figure 18**—Frequency distribution of maximum grain spirality at four heights in *latifolia* trees 152 mm in d.b.h. Each of the four bar charts represents data from 81 trees.

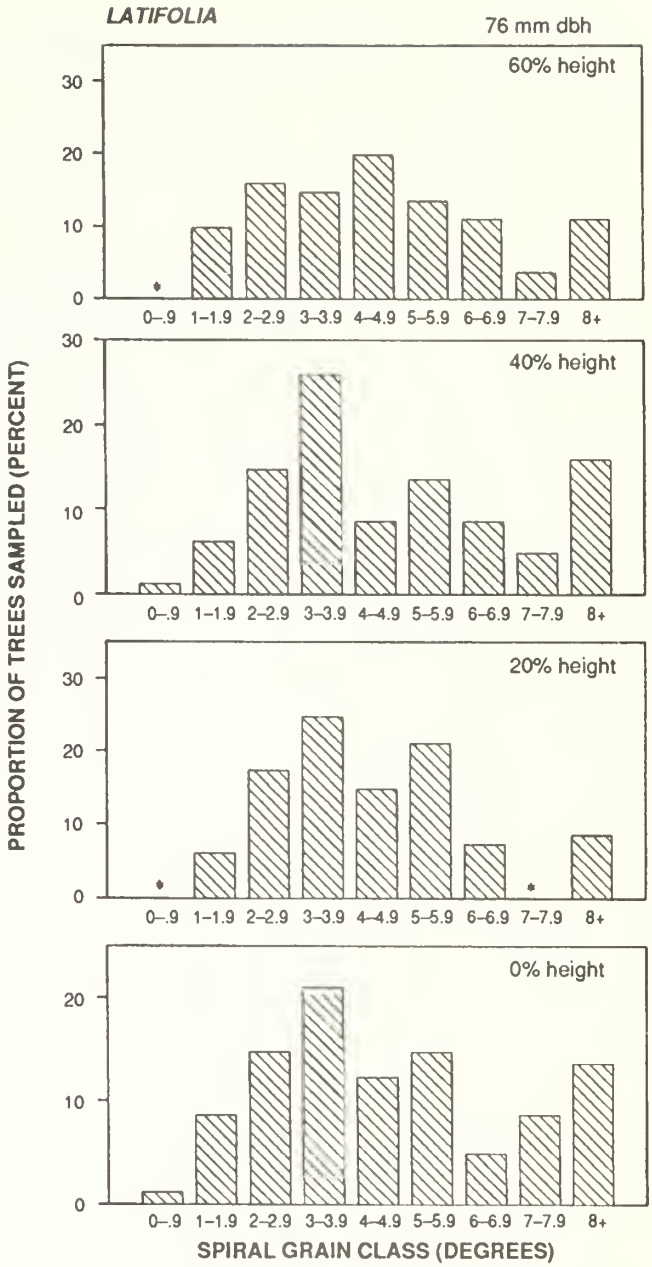



**Figure 19**—Frequency distribution of maximum grain spirality at four heights in *latifolia* trees 228 mm in d.b.h. Each of the four bar charts represents data from 81 trees. An asterisk (*) indicates none of the 81 trees had sections of the spiral grain class indicated.

Figures 16 through 19 depict the degree of maximum spirality found at various heights in the stem, and the frequency distribution of degree of spirality as a fraction of height.

Supplementary to these figures depicting degree of maximum spirality is information describing the radius from pith at which such maximums occur. In *latifolia* trees at stump height, these maximums occurred most frequently in rings more than 80 years and 80 mm from the pith (figs. 20 and 21). With increasing height in stems, the point of maximum spirality occurred increasingly closer to the pith. For example, at 60 percent of tree height one-half to three-fourths of the maximums occurred within the first 20 years of age and first 20 mm of distance from the pith (figs. 20 and 21).

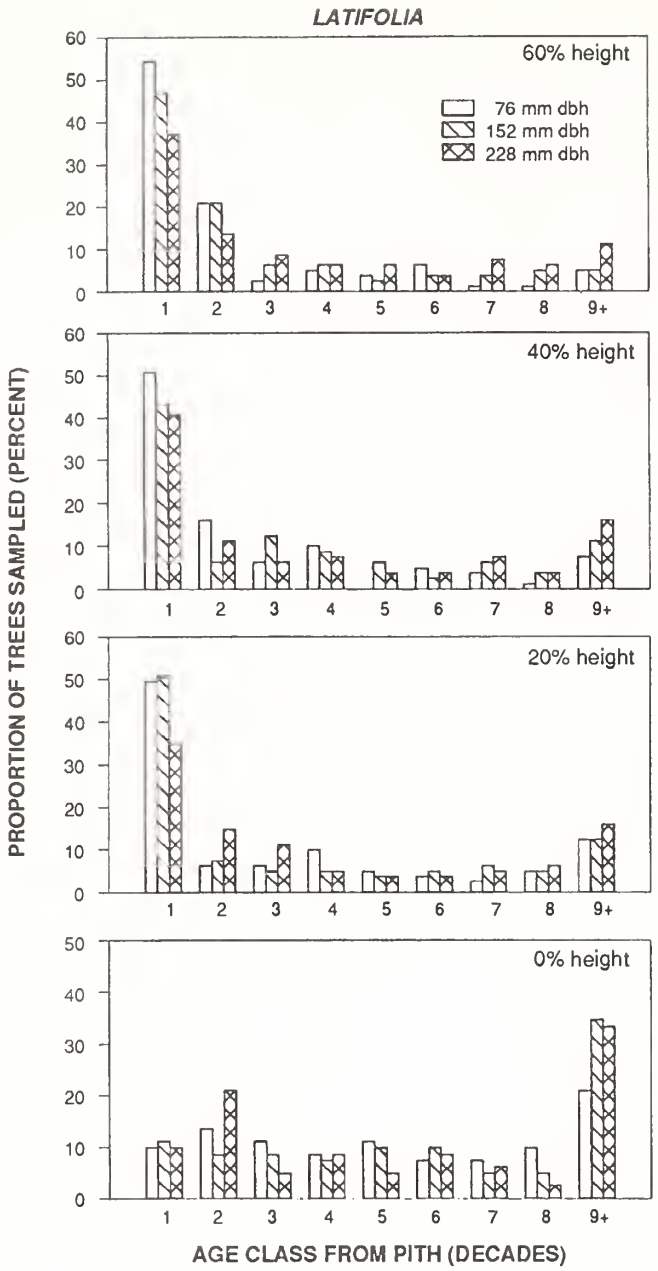



**Figure 20**—Frequency distribution of radial locations (years from pith) of point of maximum spirality at four heights in *latifolia* trees of three diameters. Each chart is defined by data from 81 trees of each diameter. Age class from pith is in decades; for example, class 2 encompasses the second decade from year 11 through year 20.

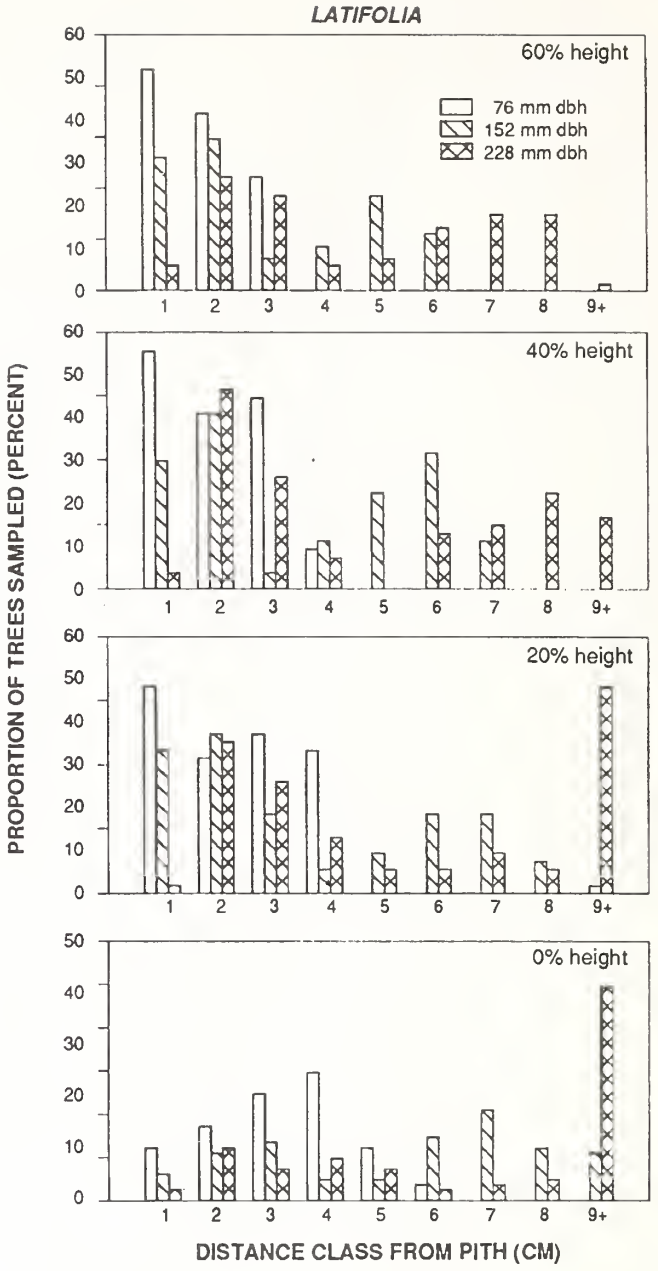



**Figure 21**—Frequency distribution of radial locations (millimeters from pith) of point of maximum spirality at four heights in *latifolia* trees of three diameters. Each chart is defined by data from 81 trees of each diameter. Distance class from pith is in centimeters; for example, class 2 encompasses the second centimeter from 11 mm through 20 mm.

Variety *murrayana* displayed radial frequency distribution patterns similar to those depicted in figures 20 and 21 for *latifolia*.

## Direction of Spirality Related to Distance From Pith and Height in Tree

Another way of visualizing the patterns of spirality is analysis of tabulations of the percentage of right-hand spirality as a function of proportion of height in tree, proportion of radius from pith to cambium, and tree d.b.h.

For both *latifolia* (table 15) and *murrayana* (table 16), the greatest percentage of right-hand spirality is found in lower stem sections in outermost stem layers; least percentage of right-hand spirality is found near the pith. For example, at ⅚ radius from stump height through 20 percent of tree height, more than 50 percent of *latifolia* trees of all three diameters had right-hand spirality. In contrast, near the pith (that is, at ⅙ radius) at 20 percent of tree height and above, less than 12 percent (mostly less than 9 percent) of the *latifolia* sections displayed right-hand spirality.

It is evident, therefore, that sawlogs from lower stem sections of both *latifolia* and *murrayana* will display about equal percentages of right-hand and left-hand spirality at log surface—but virtually all will have left-hand spirality adjacent to the pith.

The maximum degree of spirality observed in each section (at whatever radius this maximum occurred) tended toward right-handedness in lower stem sections and was predominantly left-hand in upper stem sections (tables 15 and 16).

## Direction and Degree of Spirality Related to Radius Selected (Long or Short)

When detailed spirality data were taken on one radius randomly selected on each disk, an observation was made to see whether spirality at outermost stem surface (⅚ radius) on the opposite radius had the same or different hand, that is, direction of spirality, in relation to pith alignment in the disk. For all three tree diameters and both varieties the results were similar (table 17), and are summarized as follows: At stump height slightly less than half of the sections had same-direction spirality at the cambium on opposing disk radii. This percentage increased with increasing height in the trees. From 30 through 60 percent of tree height from 152-mm-high stump top to apical tip, slightly less than two-thirds of the sections had same-direction spirality at the

**Table 15**—Percentages of right-hand spirality in stems of *latifolia* trees of three diameters related to proportion of height from 152-mm-high stump top to apical tip, and proportion of radius from pith to cambium; data are based on 81 trees of each diameter[1]

| Proportion of radius | Proportion of tree height (percent) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| | *Percent right-hand spirality* | | | | | | | | | |
| | **76 mm d.b.h.** | | | | | | | | | |
| ⅙ | 24.7 | 7.4 | 8.6 | 6.2 | 6.2 | 4.9 | 9.9 | 4.9 | 3.7 | 4.9 |
| ⅔ | 40.7 | 14.8 | 13.6 | 9.9 | 4.9 | 6.2 | 6.2 | 3.7 | 2.5 | 7.4 |
| ⅘ | 55.6 | 46.9 | 51.9 | 33.3 | 27.2 | 24.7 | 19.8 | 14.8 | 3.7 | 6.2 |
| ⅚ | 63.0 | 60.5 | 59.3 | 44.4 | 46.9 | 38.3 | 29.6 | 21.0 | 13.6 | 6.2 |
| Maximum | 51.9 | 37.0 | 37.0 | 21.0 | 23.5 | 21.0 | 17.3 | 8.6 | 6.2 | 3.7 |
| | **152 mm d.b.h.** | | | | | | | | | |
| ⅙ | 25.9 | 9.9 | 4.9 | 4.9 | 7.4 | 2.5 | 7.4 | 2.5 | 3.7 | 7.4 |
| ⅔ | 39.5 | 24.7 | 16.0 | 16.0 | 17.3 | 11.1 | 11.1 | 2.5 | 6.2 | 7.4 |
| ⅘ | 49.4 | 39.5 | 51.9 | 45.7 | 43.2 | 39.5 | 27.2 | 16.0 | 14.8 | 8.6 |
| ⅚ | 55.6 | 49.4 | 64.2 | 53.1 | 55.6 | 51.9 | 40.7 | 29.6 | 22.2 | 12.3 |
| Maximum | 46.9 | 28.4 | 35.8 | 29.6 | 35.8 | 24.7 | 23.5 | 8.6 | 16.0 | 9.9 |
| | **228 mm d.b.h.** | | | | | | | | | |
| ⅙ | 32.1 | 18.5 | 7.4 | 8.6 | 8.6 | 8.6 | 9.9 | 6.2 | 8.6 | 11.1 |
| ⅔ | 38.3 | 38.3 | 14.8 | 17.3 | 21.0 | 16.0 | 12.3 | 12.3 | 9.9 | 6.2 |
| ⅘ | 44.4 | 55.6 | 33.3 | 35.8 | 35.8 | 40.7 | 24.7 | 24.7 | 25.9 | 14.8 |
| ⅚ | 50.6 | 59.3 | 50.6 | 45.7 | 49.4 | 51.9 | 44.4 | 42.0 | 30.9 | 14.8 |
| Maximum | 44.4 | 43.2 | 28.4 | 25.9 | 37.0 | 34.6 | 25.9 | 22.2 | 21.0 | 11.1 |

[1]The rows labeled "maximum" give the average percentage of right-handed spirality at that random radius on disks where maximum spirality occurred. With data from all heights and diameters pooled, 26 percent of disks had right-hand spirality at the radius of maximum spirality.

Table 16—Percentages of right-hand spirality in stems of *murrayana* trees of three diameters related to proportion of height from 152-mm-high stump top to apical tip, and proportion of radius from pith to cambium; data are based on 12 trees of each diameter[1]

| Proportion of radius | Proportion of tree height (percent) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| | *Percent right-hand spirality* | | | | | | | | | |
| | **76 mm d.b.h.** | | | | | | | | | |
| 1/6 | 50.0 | 50.0 | 0 | 8.3 | 8.3 | 0 | 0 | 0 | 0 | 8.3 |
| 2/6 | 75.0 | 58.3 | 8.3 | 8.3 | 8.3 | 0 | 8.3 | 0 | 0 | 8.3 |
| 4/6 | 58.3 | 58.3 | 50.0 | 25.0 | 25.0 | 8.3 | 16.7 | 8.3 | 0 | 8.3 |
| 6/6 | 66.7 | 58.3 | 58.3 | 41.7 | 41.7 | 41.7 | 41.7 | 16.7 | 8.3 | 8.3 |
| Maximum | 66.7 | 66.7 | 50.0 | 33.3 | 25.0 | 25.0 | 25.0 | 8.3 | 0 | 8.3 |
| | **152 mm d.b.h** | | | | | | | | | |
| 1/6 | 25.0 | 16.7 | 16.7 | 16.7 | 0 | 8.3 | 0 | 8.3 | 0 | 8.3 |
| 2/6 | 41.7 | 58.3 | 41.7 | 33.3 | 25.0 | 16.7 | 8.3 | 0 | 0 | 0 |
| 4/6 | 58.3 | 50.0 | 58.3 | 41.7 | 25.0 | 50.0 | 16.7 | 16.7 | 0 | 0 |
| 6/6 | 58.3 | 66.7 | 66.7 | 58.3 | 58.3 | 41.7 | 25.0 | 16.7 | 8.3 | 0 |
| Maximum | 50.0 | 50.0 | 50.0 | 58.3 | 25.0 | 33.3 | 25.0 | 16.7 | 8.3 | 0 |
| | **228 mm d.b.h** | | | | | | | | | |
| 1/6 | 0 | 0 | 0 | 8.3 | 0 | 8.3 | 8.3 | 0 | 8.3 | 0 |
| 2/6 | 25.0 | 16.7 | 25.0 | 33.3 | 0 | 8.3 | 8.3 | 0 | 8.3 | 0 |
| 4/6 | 25.0 | 33.3 | 41.7 | 41.7 | 50.0 | 8.3 | 25.0 | 8.3 | 0 | 0 |
| 6/6 | 33.3 | 41.7 | 50.0 | 58.3 | 58.3 | 25.0 | 50.0 | 8.3 | 16.7 | 0 |
| Maximum | 25.0 | 41.7 | 16.7 | 41.7 | 25.0 | 0 | 16.7 | 0 | 8.3 | 0 |

[1]The rows labeled "maximum" give the average percentage of right-handed spirality at that random radius on disks where maximum spirality occurred. With data from all heights and diameters pooled, 27 percent of disks had right-hand spirality at the radius of maximum spirality.

Table 17—Percentage of disks with same-direction spirality at stem surface on opposing disk radii, related to d.b.h. and height in tree from 152-mm-high stump top to apical tip

| Proportion of height | Tree d.b.h. | | | |
|---|---|---|---|---|
| | 76 mm | 152 mm | 228 mm | Average |
| | *Percent* | | | |
| | *Latifolia* (81 trees of each d.b.h.) | | | |
| 0 | 51.9 | 43.2 | 53.1 | 49.4 |
| 10 | 55.6 | 50.6 | 64.2 | 56.8 |
| 20 | 54.3 | 53.1 | 59.3 | 55.6 |
| 30 | 55.6 | 61.7 | 71.6 | 63.0 |
| 40 | 69.1 | 66.7 | 61.7 | 65.8 |
| 50 | 64.2 | 63.0 | 66.7 | 64.6 |
| 60 | 69.1 | 66.7 | 59.3 | 65.0 |
| 70 | 74.1 | 71.6 | 65.4 | 70.4 |
| 80 | 91.4 | 79.0 | 67.9 | 79.4 |
| 90 | 95.1 | 85.2 | 84.0 | 88.1 |
| | *Murrayana* (12 trees of each d.b.h.) | | | |
| 0 | 25.0 | 41.7 | 66.7 | 44.5 |
| 10 | 58.3 | 66.7 | 66.7 | 63.9 |
| 20 | 58.3 | 50.0 | 66.7 | 58.3 |
| 30 | 75.0 | 41.7 | 66.7 | 61.1 |
| 40 | 66.7 | 50.0 | 33.3 | 50.0 |
| 50 | 83.3 | 58.3 | 66.7 | 69.4 |
| 60 | 66.7 | 58.3 | 66.7 | 63.9 |
| 70 | 75.0 | 75.0 | 58.3 | 69.4 |
| 80 | 91.7 | 75.0 | 75.0 | 80.6 |
| 90 | 75.0 | 91.7 | 100.0 | 88.9 |

cambium on opposing disk radii; and at 90 percent of tree height, nearly 90 percent had same-direction spirality (table 17).

In all sections, piths are eccentric to some degree. Opposing radii are therefore seldom the same length. When spirality just inside the cambium (6% radius) was analyzed to see if the short radius differed in direction from the long radius, it was found that no generalizations were justified. Trends by height in tree were not discernible. With all height data pooled, average proportions of disks per tree with right-hand spirality at the 6% radius on short and long radii of disks were as follows:

| D.b.h. | Short radius | Long radius |
|---|---|---|
| *mm* | *Percent* | |
| *Latifolia* (81 trees/d.b.h.; 10 disks/tree) | | |
| 76 | 37.9 | 38.3 |
| 152 | 43.7 | 43.0 |
| 228 | 47.8 | 40.3 |
| *Murrayana* 12 trees/d.b.h.; 10 disks/tree) | | |
| 76 | 34.4 | 44.3 |
| 152 | 37.0 | 44.5 |
| 228 | 34.2 | 33.2 |

In summary, it appears that there is no significant difference between short and long disk radii in proportions of disks per tree with right-hand spirality at stem surface (6% radius).

As noted previously, detailed analysis of disk spirality alternated randomly between short and long disk radii, thus providing an opportunity to assess whether spirality was greater on the short or the long radius. Averages for all heights (table 18) suggest that greatest spirality tends to occur on long, rather than short, disk radii, as follows:

| D.b.h. | *Latifolia* | | *Murrayana* | |
|---|---|---|---|---|
| | Short | Long | Short | Long |
| *mm* | *Average maximum spirality, degrees* | | | |
| 76 | 3.49 | 3.62 | 3.64 | 3.43 |
| 152 | 4.07 | 4.10 | 4.06 | 4.54 |
| 228 | 4.69 | 4.88 | 4.42 | 5.19 |

The trend is weak, however, as seen from averages by heights with tree-d.b.h. data pooled (table 18).

**Table 18**—Comparison of maximum spirality averages observed along short and long disk radii related to height in trees of three diameters[1]

| Proportion of height | 76 mm d.b.h. | | 152 mm d.b.h. | | 228 mm d.b.h. | | Weighted average | |
|---|---|---|---|---|---|---|---|---|
| | Short | Long | Short | Long | Short | Long | Short | Long |
| *Percent* | *Average of maximum disk spirality, degrees* | | | | | | | |
| | ***Latifolia* (81 trees of each d.b.h.)** | | | | | | | |
| 0 | 4.27 | 3.99 | 4.55 | 5.05 | 5.43 | 4.67 | 4.77 | 4.54 |
| | (35) | (46) | (42) | (39) | (40) | (41) | (117) | (126) |
| 10 | 3.49 | 3.43 | 3.95 | 3.61 | 3.48 | 5.47 | 3.64 | 4.13 |
| | (34) | (47) | (37) | (44) | (39) | (42) | (110) | (133) |
| 20 | 3.11 | 3.09 | 3.93 | 3.67 | 4.22 | 4.62 | 3.72 | 3.84 |
| | (42) | (39) | (39) | (42) | (35) | (46) | (116) | (127) |
| 30 | 3.43 | 3.38 | 4.40 | 4.02 | 4.41 | 4.78 | 4.09 | 4.05 |
| | (36) | (45) | (39) | (42) | (38) | (43) | (113) | (130) |
| 40 | 3.83 | 3.79 | 4.18 | 3.80 | 5.08 | 5.33 | 4.38 | 4.29 |
| | (38) | (43) | (39) | (42) | (41) | (40) | (118) | (125) |
| 50 | 3.67 | 3.83 | 3.88 | 4.25 | 5.17 | 4.75 | 4.23 | 4.28 |
| | (36) | (45) | (39) | (42) | (36) | (45) | (111) | (132) |
| 60 | 3.23 | 3.48 | 4.03 | 3.93 | 4.64 | 4.96 | 3.92 | 4.16 |
| | (41) | (40) | (38) | (43) | (34) | (47) | (113) | (130) |
| 70 | 3.27 | 3.78 | 3.47 | 4.19 | 4.72 | 4.74 | 3.88 | 4.21 |
| | (38) | (43) | (36) | (45) | (45) | (36) | (119) | (124) |
| 80 | 3.67 | 4.14 | 4.42 | 4.27 | 5.27 | 4.68 | 4.43 | 4.37 |
| | (39) | (42) | (37) | (44) | (36) | (45) | (112) | (131) |
| 90 | 3.03 | 3.23 | 3.84 | 4.29 | 4.51 | 4.84 | 3.84 | 4.07 |
| | (35) | (46) | (40) | (41) | (43) | (38) | (118) | (125) |
| Weighted average | 3.49 | 3.62 | 4.07 | 4.10 | 4.69 | 4.88 | 4.09 | 4.19 |
| | (374) | (436) | (386) | (424) | (387) | (423) | (1,147) | (1,283) |
| | ***Murrayana* (12 trees of each d.b.h.)** | | | | | | | |
| 0 | 4.88 | 6.28 | 5.38 | 6.52 | 6.40 | 8.28 | 5.55 | 7.03 |
| | (6) | (6) | (6) | (6) | (6) | (6) | (18) | (18) |
| 10 | 2.70 | 5.20 | 5.35 | 4.23 | 4.36 | 4.04 | 4.23 | 4.55 |
| | (5) | (7) | (6) | (6) | (7) | (5) | (18) | (18) |
| 20 | 4.25 | 3.55 | 3.88 | 4.42 | 3.52 | 5.27 | 3.88 | 4.41 |
| | (6) | (6) | (6) | (6) | (6) | (6) | (18) | (18) |
| 30 | 5.10 | 2.73 | 3.48 | 4.40 | 4.74 | 3.83 | 4.42 | 3.66 |
| | (6) | (6) | (6) | (6) | (5) | (7) | (17) | (19) |
| 40 | 3.44 | 3.18 | 4.74 | 3.78 | 4.27 | 5.17 | 4.14 | 4.11 |
| | (7) | (5) | (7) | (5) | (6) | (6) | (20) | (16) |
| 50 | 3.30 | 2.36 | 2.46 | 4.40 | 4.64 | 4.69 | 3.47 | 3.82 |
| | (5) | (7) | (5) | (7) | (5) | (7) | (15) | (21) |
| 60 | 3.31 | 3.06 | 4.01 | 2.96 | 3.56 | 5.56 | 3.63 | 3.86 |
| | (7) | (5) | (7) | (5) | (7) | (5) | (21) | (15) |
| 70 | 4.33 | 2.92 | 2.68 | 5.16 | 4.77 | 4.60 | 4.08 | 4.32 |
| | (6) | (6) | (4) | (8) | (6) | (6) | (16) | (20) |
| 80 | 2.93 | 2.84 | 4.51 | 3.33 | 3.71 | 6.84 | 3.75 | 4.41 |
| | (7) | (5) | (8) | (4) | (7) | (5) | (22) | (14) |
| 90 | 2.15 | 1.87 | 3.08 | 5.25 | 4.60 | 4.24 | 3.20 | 3.81 |
| | (6) | (6) | (6) | (6) | (5) | (7) | (17) | (19) |
| Weighted average | 3.64 | 3.43 | 4.06 | 4.54 | 4.42 | 5.19 | 4.04 | 4.39 |
| | (61) | (59) | (61) | (59) | (60) | (60) | (182) | (178) |

[1]Entries in the table show the mean; listed in parentheses below the mean is the number of observations.

## Spirality Correlated With Ring Width, and Age and Distance From Pith

Degree of spirality in both *latifolia* and *murrayana* was poorly correlated with width of annual ring in which spirality was measured. Because ring width diminished in these trees with increasing age and distance from pith, it was difficult to isolate spirality relationships with ring width as distinct from ring age from pith.

There were, however, some discernible trends relating degree and direction of spirality to ring age from pith in *latifolia*. To see these trends it was useful to segregate disk data by major spirality patterns (fig. 22). These three major patterns (1, 1A, and 3) accounted for nearly four-fifths of the patterns observed (fig. 8) in individual *latifolia* disks.

When data from all 243 *latifolia* trees (2,430 disks) and all 36 *murrayana* trees (360 disks) were pooled by variety, and data averaged by age from pith in decades or distance from pith in centimeters, significant relationships were evident (figs. 23 and 24), as follows:

*Latifolia:*

$Y = 2.277 - 0.308X$

$r = -0.962$; standard error of the estimate = 0.355 degrees

$Y = 1.623 - 0.12Z$

$r = -0.633$; standard error of the estimate = 0.597 degrees

*Murrayana:*

$Y = 2.764 - 0.452X$

$r = -0.942$; standard error of the estimate = 0.515 degrees

$Y = 2.437 - 0.277Z$

$r = -0.850$; standard error of the estimate = 0.551 degrees

where:

$Y$ = angle of spirality, degrees; positive is left-hand, negative is right-hand

$X$ = age class from pith, decades

$Z$ = distance class from pith, centimeters.

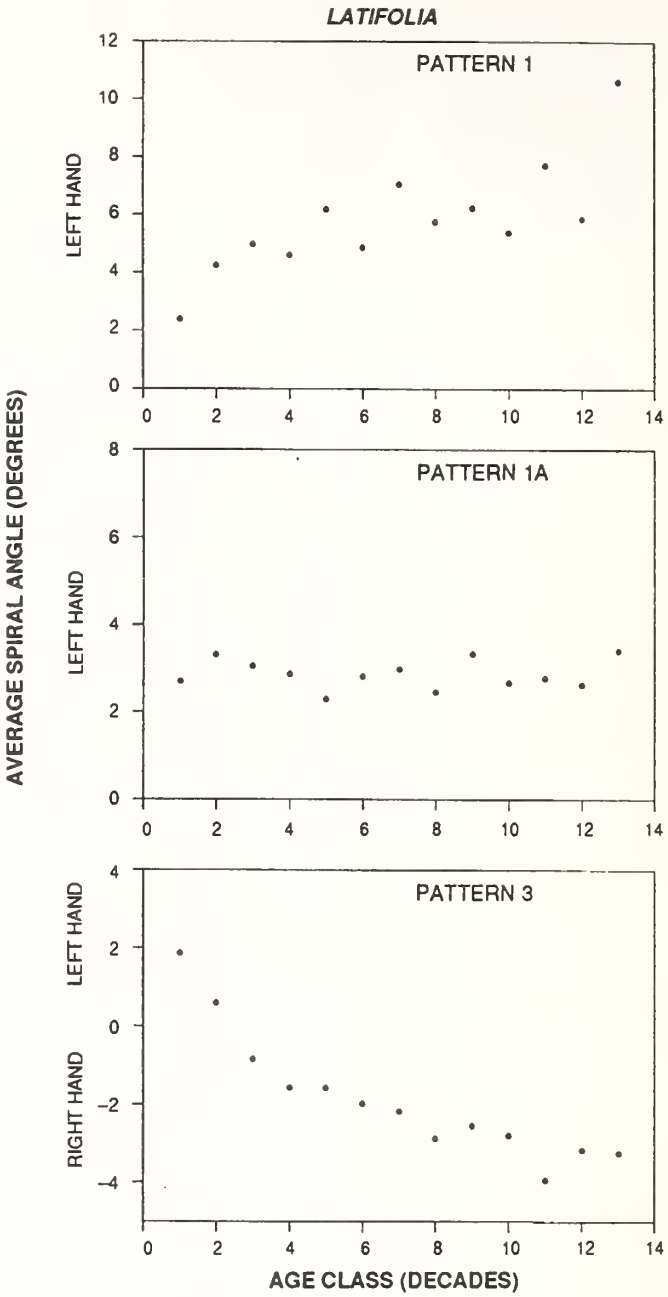



**Figure 22**—Variation of spirality in *latifolia* with age class from pith for disk spirality patterns 1, 1A, and 3 (see fig. 8 for definitions). These three patterns accounted for 78.4 percent of all spirality patterns observed (pattern 1, 17.1 percent; pattern 1A, 25.9 percent; and pattern 3, 35.4 percent). On the horizontal axis numbers indicate age class from pith in decades; that is, 2 indicates 10 years through 19 years, 3 indicates 20 years through 29 years, etc.

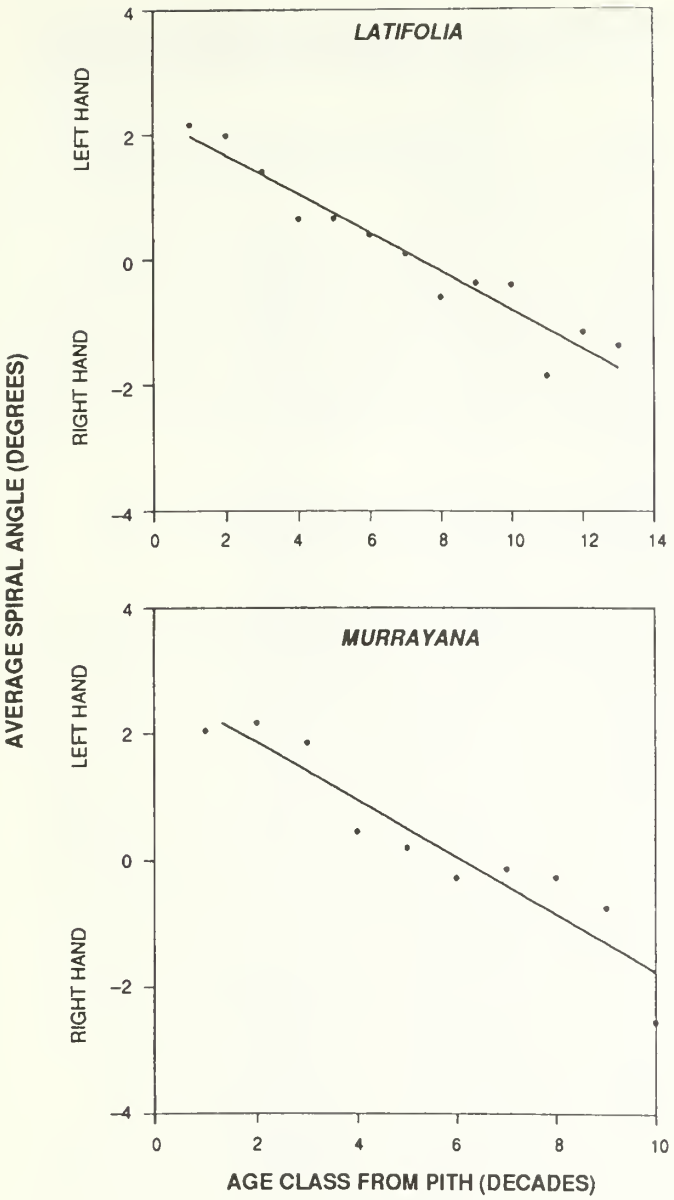



**Figure 23**—Variation of spirality in annual rings of *latifolia* and *murrayana* related to age class from pith. On the horizontal axis numbers indicate age class from pith in decades; that is, 2 indicates 10 years through 19 years, 3 indicates 20 years through 29 years, etc.

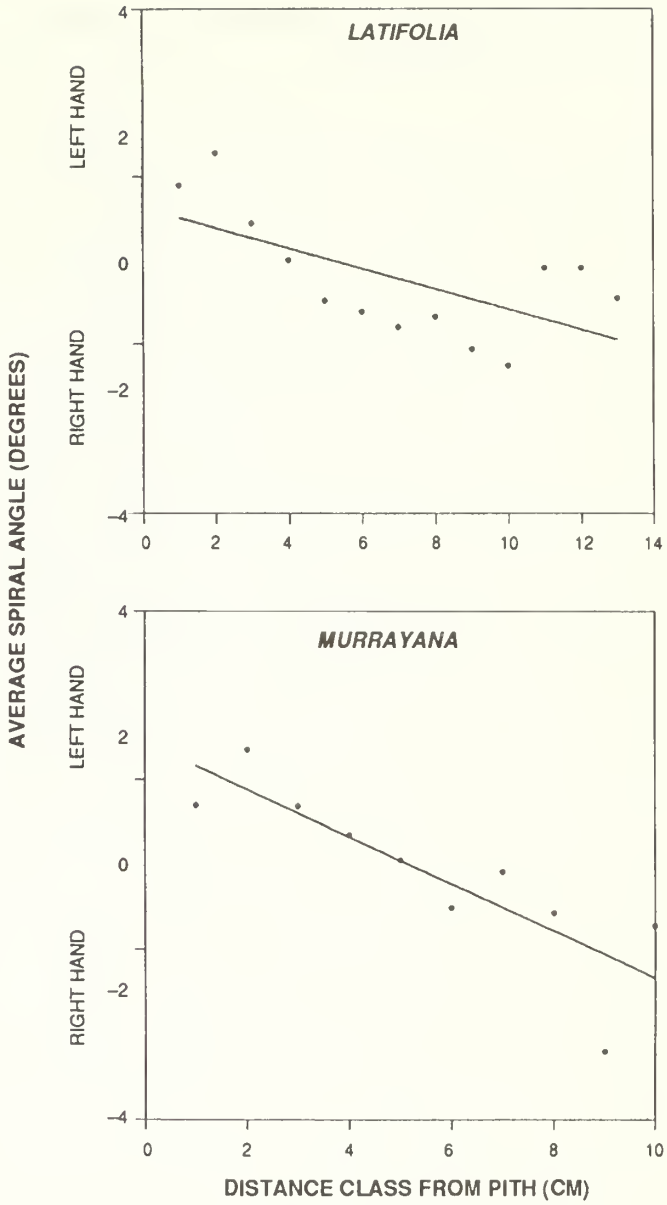



**Figure 24**—Variation of spirality in *latifolia* and *murrayana* with distance from pith. On the horizontal axis numbers indicate distance class from pith, that is, 2 indicates 10 mm through 19 mm, 3 indicates 20 mm through 29 mm, etc.

## Disk Properties Correlated With Disk Maximum Spirality

As previously noted in discussions related to table 4, when entire stems of *latifolia* trees were evaluated, greatest tree-average spirality was found in old, large-diameter, heavy trees with heavy stump-root systems, much heartwood and eccentric piths in stems, many cones, and long, wide crowns comprised of many thick-barked large-diameter branches bearing much foliage. Spirality tends to be greater in extreme north and south latitudes than at midlatitudes of the species' range. In the 243 *latifolia* trees examined, variation was substantial; volume-weighted, tree-average maximum spiral grain ranged from 1.5 degrees to 10.7 degrees.

From previous and ongoing work, numerous disk-average properties are available for the 243 *latifolia* trees (2,430 disks) under study. To supplement the findings under the immediately preceding heading, an effort was made to find significant correlations between some of these disk properties and maximum degree of spirality observed in each disk. Ten of the 13 correlations examined were statistically significant (0.05 level) as follows:

| Disk-average property | *r* | *p-value* |
|---|---|---|
| Pith eccentricity (millimeters) | 0.1602 | 0.0001 |
| Stem bark thickness | .1537 | .0001 |
| Heartwood percentage of stemwood volume | .1286 | .0001 |
| Latewood tangential lumen diameter | .0808 | .0001 |
| Latewood tangential cell diameter | .0803 | .0001 |
| Earlywood fiber length | .0770 | .0001 |
| Stemwood moisture content (percent of ovendry weight) | –.0756 | .0002 |
| Stemwood out-of-roundness index as defined by Koch and others (1990) | –.0656 | .0012 |
| Earlywood tangential cell diameter | .0627 | .0020 |
| Earlywood tangential lumen diameter | .0612 | .0025 |
| Not Significant | | |
| Volumetric percentage of compression wood | .02055 | .3113 |
| Specific gravity (ovendry weight and green volume) | .00004 | .9982 |
| Latewood fiber length | .03467 | .0875 |

The foregoing significant correlations are very weak, but suggest that greatest maximum spirality—sign ignored—may be found in thick-barked, out-of-round sections of low moisture content but high heartwood content, and with eccentric piths. Additionally, greatest maximum spirality may be found in sections with large tangential cell diameters and long earlywood fibers.

## Disk-Average Ring Width Related to Height in Tree

When data from all heights and tree diameters were averaged (but not volume-weighted), annual growth rings averaged wider in *murrayana* (1.58 mm) than in *latifolia* (1.18 mm). In both varieties disk-average growth ring width was positively correlated with both tree d.b.h. and height in tree (table 19 and and fig. 25).

## Ring Width Related to Radius and Height at Which Sampled

At every height in *latifolia* trees of all diameters, annual growth-ring width was greatest near the pith and diminished toward the bark (table 20 and figs. 12, 26, and 27). At ⅙ and ⅔ of the radial distance from pith to bark, ring width was maximum at 20 to 50 percent of tree height. At ⅓ and ⅚ radii, however, ring width decreased slightly from stump-top height (0 percent of tree height) to about 20 percent of tree height and then increased with increasing height in trees. At 90 percent of tree height, ring widths were more nearly equal at all radii (0.7 mm to 1.6 mm) than at other heights in the trees (fig. 26). As previously noted, our procedure for tree selection from unthinned natural stands yielded trees of 76 mm and 152 mm that were more-or-less suppressed. Data for the 228-mm trees are representative of more dominant and less suppressed trees.

It is worth noting and emphasizing that at ⅚ radius, growth-ring widths in *latifolia* trees of all three diameters averaged significantly less than 1 mm except in uppermost stem sections of the larger trees (fig. 26). With data from all 243 *latifolia* trees (2,430 disks) pooled by age in decades, a smooth asymptotic allometric relationship (of the form $Y = aX^b$) was found in which ring width ($Y$) approached 0.3 mm in the 10th decade and beyond (fig. 27), as follows:

$$Y = 1.8841X^{-0.611}$$

where

$X$ = age class, decades.

The linearized form of this equation ($\ln Y = \ln a + b \ln X$) has $R^2 = 0.97$, with standard error of the estimate = 0.082 degrees.

**Table 19**—Disk-average width of annual rings in *latifolia* trees of three diameters related to proportion of height in tree[1]

| Proportion of height | Tree d.b.h. 76 mm | 152 mm | 228 mm |
|---|---|---|---|
| *Percent* | - - - - - - - - - - - - - - - - *mm* - - - - - - - - - - - - - - - - | | |
| ***Latifolia* (data based on 81 trees of each d.b.h.)** | | | |
| 0 | 0.69(0.41) | 1.02(0.39) | 1.39(0.52) |
| | 0.19-2.52 | 0.32-2.15 | 0.48-2.76 |
| 10 | 0.72(0.44) | 1.00(0.42) | 1.29(0.49) |
| | 0.18-3.08 | 0.30-2.25 | 0.49-2.49 |
| 20 | 0.77(0.50) | 1.06(0.46) | 1.34(0.54) |
| | 0.20-3.45 | 0.33-2.38 | 0.50-3.14 |
| 30 | 0.82(0.55) | 1.10(0.50) | 1.38(0.59) |
| | 0.23-3.50 | 0.33-2.56 | 0.53-3.67 |
| 40 | 0.87(0.57) | 1.15(0.54) | 1.43(0.62) |
| | 0.23-3.41 | 0.38-2.82 | 0.55-3.67 |
| 50 | 0.89(0.63) | 1.22(0.59) | 1.47(0.66) |
| | 0.21-3.54 | 0.42-3.03 | 0.53-3.90 |
| 60 | 0.93(0.67) | 1.29(0.63) | 1.52(0.69) |
| | 0.22-3.54 | 0.41-3.20 | 0.59-3.85 |
| 70 | 0.97(0.72) | 1.35(0.66) | 1.56(0.74) |
| | 0.22-4.00 | 0.41-3.31 | 0.60-3.57 |
| 80 | 1.01(0.72) | 1.43(0.71) | 1.57(0.77) |
| | 0.16-3.44 | 0.40-3.44 | 0.67-4.56 |
| 90 | 1.02(0.69) | 1.54(0.87) | 1.52(0.74) |
| | 0.15-3.00 | 0.45-5.18 | 0.51-3.50 |
| All heights | 0.87(0.61) | 1.21(0.62) | 1.45(0.65) |
| | 0.15-4.00 | 0.30-5.18 | 0.48-4.56 |
| ***Murrayana* (data based on 12 trees of each d.b.h.)** | | | |
| 0 | 0.71(0.32) | 1.18(0.49) | 1.67(0.63) |
| | 0.36-1.41 | 0.54-1.96 | 0.89-2.87 |
| 10 | 0.78(0.34) | 1.19(0.48) | 1.64(0.63) |
| | 0.39-1.55 | 0.53-2.04 | 0.90-2.71 |
| 20 | 0.86(0.33) | 1.30(0.55) | 1.73(0.60) |
| | 0.44-1.55 | 0.59-2.35 | 0.97-2.72 |
| 30 | 0.95(0.36) | 1.41(0.65) | 1.86(0.68) |
| | 0.43-1.64 | 0.61-2.46 | 1.03-2.99 |
| 40 | 1.06(0.43) | 1.57(0.78) | 1.95(0.74) |
| | 0.41-1.79 | 0.63-3.12 | 1.02-3.14 |
| 50 | 1.13(0.43) | 1.67(0.86) | 2.08(0.76) |
| | 0.40-1.86 | 0.65-3.43 | 1.07-3.21 |
| 60 | 1.15(0.43) | 1.82(1.04) | 2.28(0.85) |
| | 0.35-1.96 | 0.68-4.25 | 1.09-3.74 |
| 70 | 1.26(0.47) | 1.95(1.15) | 2.37(0.81) |
| | 0.46-1.97 | 0.75-4.71 | 1.10-3.62 |
| 80 | 1.36(0.51) | 2.09(1.05) | 2.44(0.92) |
| | 0.52-1.93 | 0.97-4.08 | 1.04-3.94 |
| 90 | 1.48(0.52) | 2.18(1.02) | 2.38(0.88) |
| | 0.63-2.58 | 0.81-3.50 | 1.03-3.60 |
| All heights | 1.07(0.47) | 1.64(0.88) | 2.04(0.79) |
| | 0.35-2.58 | 0.53-4.71 | 0.89-3.94 |

[1]Entries in the body of the table show the mean, followed by the standard deviation; listed below these statistics is the range of values.

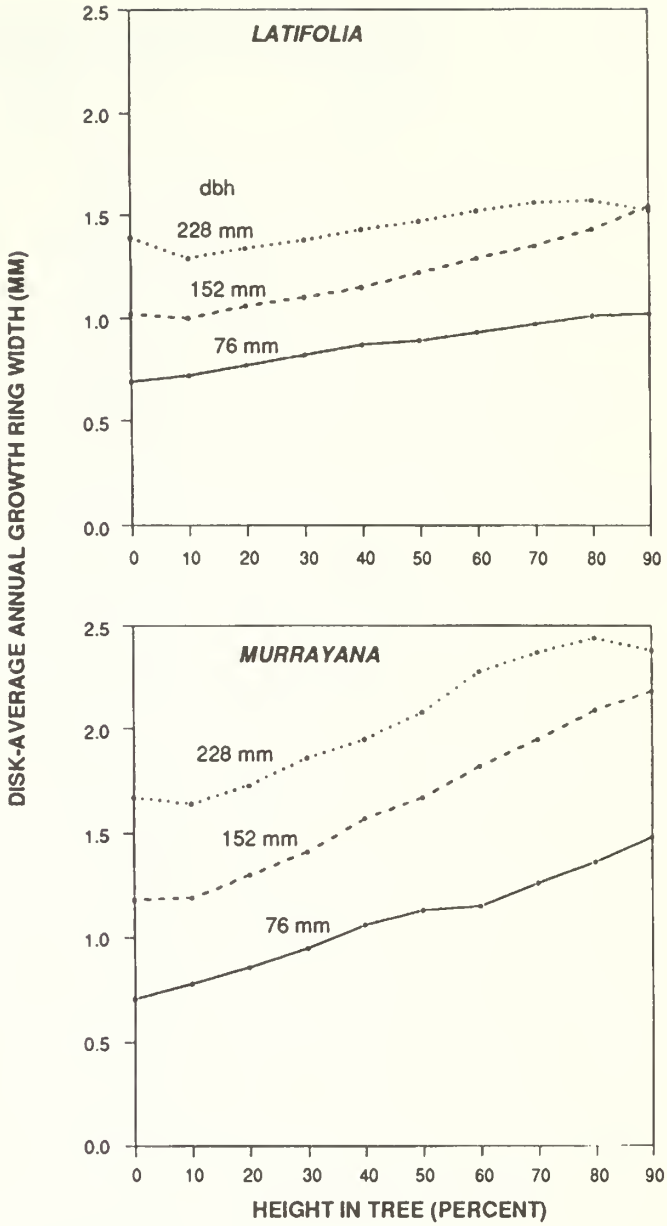



**Figure 25**—Disk-average annual growth ring width in *latifolia* and *murrayana* trees of three diameters related to proportion of height in tree from 152-mm-high stump top to apical tip.

**Table 20**—Ring width in *latifolia* trees of three diameters, related to proportions of height in tree, and radial distance from pith to cambium[1]

| Proportion of height | Proportion of radius from pith to cambium | | | |
|---|---|---|---|---|
| | 1/6 | 2/6 | 4/6 | 6/6 |
| *Percent* | *mm* | | | |
| | **76 mm d.b.h.** | | | |
| 0 | 1.08(0.45) | 1.00(0.59) | 0.74(0.45) | 0.48(0.49) |
| | 0.3-2.3 | 0.1-3.0 | 0.2-3.0 | 0.1-2.7 |
| 10 | 1.44(0.60) | 1.12(0.62) | 0.77(0.54) | 0.44(0.43) |
| | 0.4-3.3 | 0.2-3.2 | 0.2-2.9 | 0.1-2.5 |
| 20 | 1.51(0.63) | 1.28(0.71) | 0.77(0.52) | 0.43(0.42) |
| | 0.3-4.3 | 0.1-4.4 | 0.1-3.3 | 0.1-2.4 |
| 30 | 1.46(0.57) | 1.33(0.65) | 0.80(0.53) | 0.45(0.44) |
| | 0.3-3.1 | 0.2-3.1 | 0.1-2.6 | 0.1-2.3 |
| 40 | 1.52(0.60) | 1.37(0.69) | 0.86(0.58) | 0.53(0.57) |
| | 0.3-3.3 | 0.3-3.5 | 0.1-3.1 | 0.1-3.1 |
| 50 | 1.47(0.62) | 1.37(0.67) | 0.86(0.60) | 0.52(0.60) |
| | 0.3-3.2 | 0.2-3.2 | 0.1-3.0 | 0.1-3.0 |
| 60 | 1.43(0.63) | 1.36(0.66) | 0.83(0.59) | 0.59(0.60) |
| | 0.2-3.1 | 0.2-3.1 | 0.2-3.0 | 0.1-3.0 |
| 70 | 1.28(0.57) | 1.15(0.63) | 0.87(0.60) | 0.67(0.65) |
| | 0.3-3.1 | 0.1-3.1 | 0.1-2.6 | 0.1-2.7 |
| 80 | 1.26(0.50) | 1.17(0.57) | 0.93(0.65) | 0.77(0.70) |
| | 0.3-2.8 | 0.2-2.8 | 0.1-2.8 | 0.1-2.8 |
| 90 | 1.05(0.47) | 1.02(0.50) | 0.87(0.56) | 0.77(0.61) |
| | 0.2-2.4 | 0.2-2.4 | 0.2-2.4 | 0.1-2.4 |
| All | 1.35(0.59) | 1.22(0.64) | 0.83(0.56) | 0.56(0.57) |
| | 0.2-4.3 | 0.1-4.4 | 0.1-3.3 | 0.1-3.1 |
| | **152 mm d.b.h.** | | | |
| 0 | 1.51(0.68) | 1.46(0.71) | 1.04(0.64) | 0.64(0.49) |
| | 0.1-3.1 | 0.2-3.3 | 0.1-3.3 | 0.1-2.2 |
| 10 | 2.10(0.89) | 1.74(0.86) | 0.93(0.51) | 0.61(0.42) |
| | 0.3-4.7 | 0.3-4.3 | 0.3-2.6 | 0.1-1.9 |
| 20 | 2.24(0.87) | 1.80(0.88) | 0.96(0.49) | 0.60(0.39) |
| | 0.6-4.3 | 0.2-4.6 | 0.2-2.6 | 0.1-1.9 |
| 30 | 2.21(0.74) | 1.81(0.82) | 0.99(0.61) | 0.62(0.47) |
| | 0.4-4.0 | 0.2-4.5 | 0.2-3.5 | 0.1-2.4 |
| 40 | 2.17(0.77) | 1.84(0.85) | 1.04(0.57) | 0.63(0.47) |
| | 0.5-4.0 | 0.3-4.2 | 0.3-2.8 | 0.1-2.2 |
| 50 | 2.07(0.71) | 1.80(0.74) | 1.14(0.63) | 0.70(0.54) |
| | 0.4-3.3 | 0.3-4.1 | 0.2-3.1 | 0.1-2.3 |
| 60 | 1.94(0.69) | 1.75(0.76) | 1.22(0.72) | 0.83(0.73) |
| | 0.7-3.7 | 0.3-3.7 | 0.2-3.6 | 0.1-3.7 |
| 70 | 1.74(0.66) | 1.70(0.75) | 1.25(0.71) | 0.90(0.70) |
| | 0.5-4.0 | 0.4-4.0 | 0.3-3.9 | 0.1-3.8 |
| 80 | 1.61(0.61) | 1.57(0.66) | 1.34(0.74) | 1.06(0.80) |
| | 0.3-3.4 | 0.5-3.4 | 0.2-4.0 | 0.2-4.0 |
| 90 | 1.53(0.57) | 1.51(0.61) | 1.31(0.71) | 1.18(0.78) |
| | 0.5-3.0 | 0.5-3.0 | 0.3-3.0 | 0.2-3.0 |
| All | 1.91(0.77) | 1.70(0.76) | 1.12(0.65) | 0.78(0.63) |
| | 0.1-4.7 | 0.2-4.6 | 0.1-4.0 | 0.1-4.0 |
| | **228 mm d.b.h.** | | | |
| 0 | 1.91(0.83) | 1.93(0.88) | 1.35(0.73) | 0.83(0.59) |
| | 0.4-4.5 | 0.5-4.3 | 0.3-3.7 | 0.1-3.0 |
| 10 | 2.52(1.08) | 1.97(0.93) | 1.16(0.52) | 0.72(0.49) |
| | 0.5-5.5 | 0.2-4.5 | 0.3-2.7 | 0.1-2.5 |
| 20 | 2.75(1.09) | 2.22(1.1) | 1.20(0.57) | 0.73(0.44) |
| | 0.5-6.0 | 0.5-5.6 | 0.3-3.2 | 0.1-2.0 |
| 30 | 2.74(1.0) | 2.25(1.08) | 1.24(0.67) | 0.72(0.45) |
| | 0.4-5.1 | 0.5-5.0 | 0.3-3.9 | 0.1-2.5 |
| 40 | 2.67(0.86) | 2.12(0.84) | 1.27(0.65) | 0.70(0.44) |
| | 0.8-4.5 | 0.5-4.9 | 0.3-3.6 | 0.1-2.6 |
| 50 | 2.51(0.92) | 2.23(0.89) | 1.33(0.68) | 0.81(0.58) |
| | 0.6-4.5 | 0.5-4.5 | 0.3-3.7 | 0.2-3.1 |
| 60 | 2.31(0.93) | 2.20(0.99) | 1.40(0.73) | 0.85(0.63) |
| | 0.6-4.7 | 0.5-5.6 | 0.5-3.8 | 0.2-3.8 |
| 70 | 2.13(0.80) | 2.01(0.88) | 1.41(0.83) | 0.90(0.67) |
| | 0.6-4.3 | 0.6-4.5 | 0.4-3.8 | 0.2-3.8 |
| 80 | 1.90(0.63) | 1.80(0.79) | 1.46(0.79) | 1.10(0.80) |
| | 0.8-3.6 | 0.6-4.0 | 0.5-3.6 | 0.2-3.5 |
| 90 | 1.63(0.66) | 1.53(0.72) | 1.35(0.74) | 1.14(0.76) |
| | 0.6-4.0 | 0.5-4.0 | 0.4-4.0 | 0.2-4.0 |
| All | 2.31(0.96) | 2.03(0.94) | 1.32(0.70) | 0.85(0.61) |
| | 0.4-6.0 | 0.2-5.6 | 0.3-4.0 | 0.1-4.0 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total trees in the sample = 243, that is, 81 of each d.b.h.

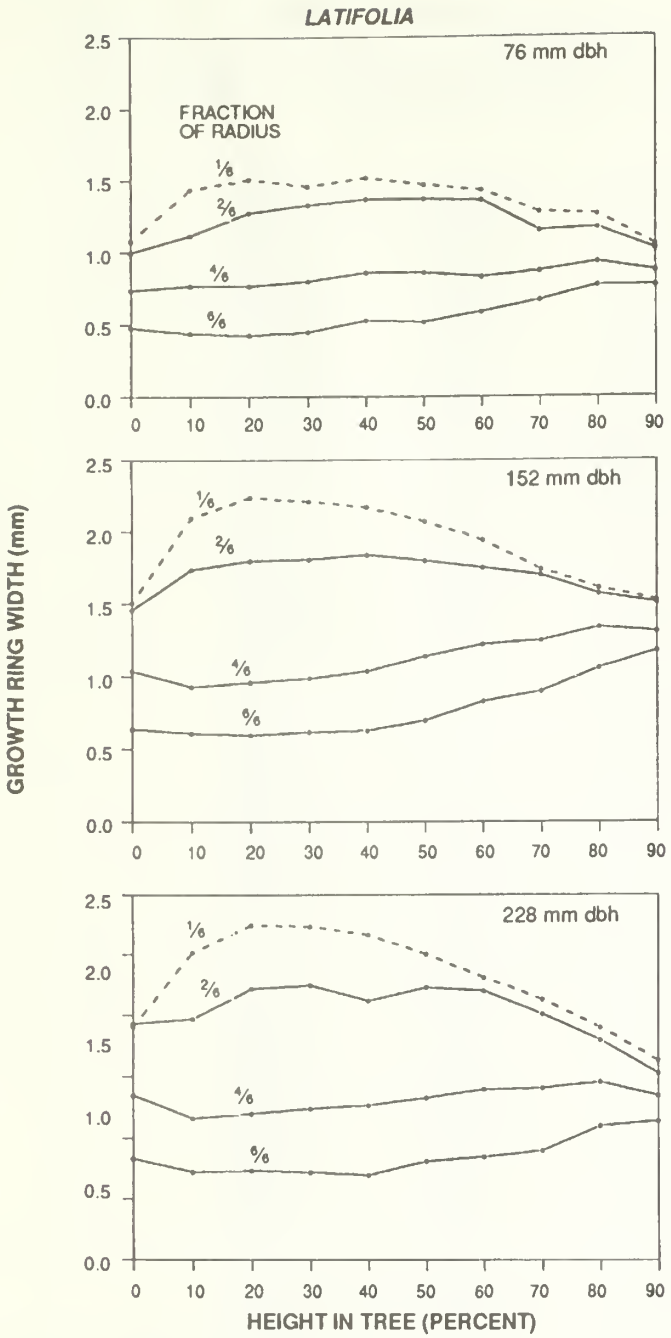



**Figure 26**—Annual growth-ring width in *latifolia* trees of three diameters related to proportions of height in tree and radial distance from pith to bark. Each point on each line is defined by data from 81 trees.

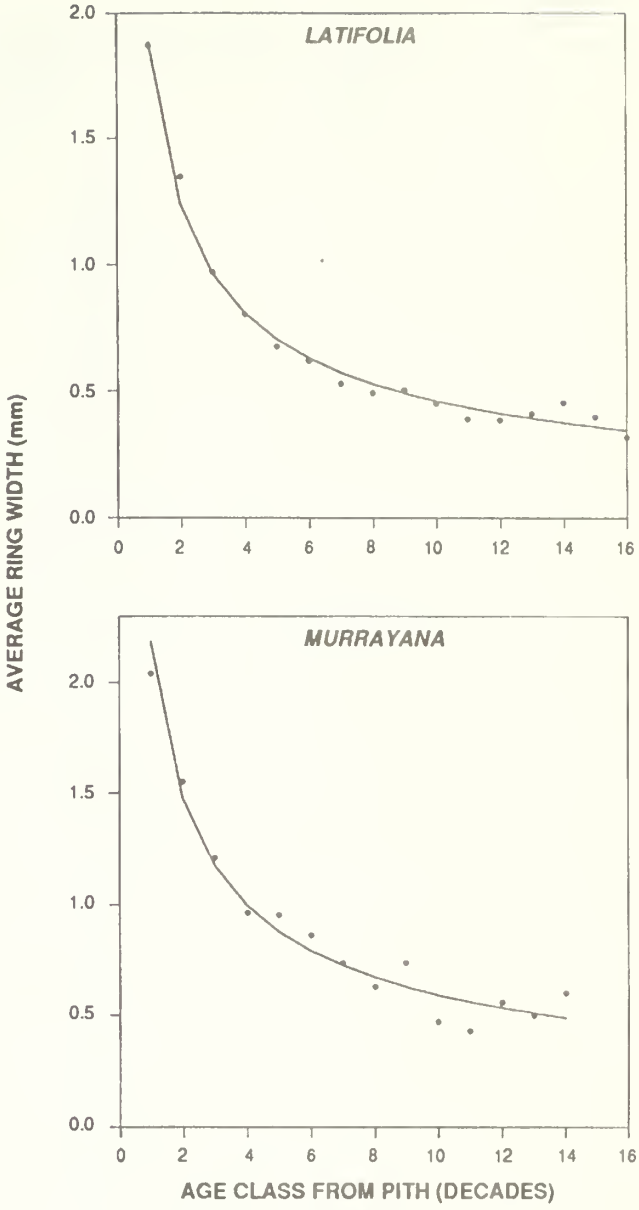



**Figure 27**—Average annual growth ring width in *latifolia* (243 trees, 2,430 disks—4 radii/disk) and *murrayana* (36 trees, 360 disks—4 radii/disk) related to age from pith—data pooled by decades. Numbers on the horizontal axis denote decades; that is, 1 denotes years 0 through 9, 2 denotes years 10 through 19, etc.

Our sample of *murrayana* was small (12 trees per diameter) and resulting data (table 21 and fig. 28) yielded graphs less clearly defined than those for *latifolia*. Both varieties displayed the same general characteristics, however; that is, at all heights annual growth-ring width was greatest near the pith and diminished toward the bark and with increased age from the pith (figs. 27 and 28). Ring width at all radii increased with increasing height in tree and in uppermost tree portions converged to values in the range from 1.2 mm to 2.1 mm—the convergence value positively correlated with d.b.h. As with *latifolia*, small-diameter trees had narrower growth rings than large-diameter trees.

**Table 21**—Ring width in *murrayana* trees of three diameters, related to proportions of height in tree, and radial distance from pith to cambium[1]

| Proportion of height | Proportion of radius from pith to cambium | | | |
|---|---|---|---|---|
| | 1/6 | 2/6 | 4/6 | 5/6 |
| *Percent* | *mm* | | | |
| | **76 mm d.b.h.** | | | |
| 0 | 1.11(0.59) | 1.06(0.45) | 0.73(0.14) | 0.43(0.19) |
| | 0.2-2.0 | 0.6-2.0 | 0.6-1.1 | 0.2-0.8 |
| 10 | 1.48(0.64) | 1.08(0.44) | 0.83(0.43) | 0.51(0.42) |
| | 0.3-2.3 | 0.5-1.8 | 0.3-1.7 | 0.1-1.6 |
| 20 | 1.32(0.41) | 1.23(0.52) | 0.78(0.31) | 0.47(0.26) |
| | 0.7-2.0 | 0.4-1.8 | 0.2-1.3 | 0.2-1.0 |
| 30 | 1.49(0.48) | 1.28(0.57) | 0.89(0.58) | 0.60(0.62) |
| | 0.7-2.2 | 0.4-2.2 | 0.2-2.1 | 0.1-2.3 |
| 40 | 1.29(0.43) | 1.26(0.38) | 0.92(0.29) | 0.52(0.23) |
| | 0.6-2.0 | 0.6-1.9 | 0.4-1.4 | 0.2-0.9 |
| 50 | 1.45(0.37) | 1.44(0.57) | 1.04(0.60) | 0.81(0.67) |
| | 0.8-1.9 | 0.5-2.4 | 0.3-2.6 | 0.2-2.4 |
| 60 | 1.27(0.49) | 1.24(0.55) | 0.99(0.36) | 0.75(0.38) |
| | 0.3-2.2 | 0.2-2.2 | 0.5-1.8 | 0.2-1.3 |
| 70 | 1.28(0.48) | 1.32(0.57) | 1.09(0.54) | 1.06(0.60) |
| | 0.5-2.3 | 0.4-2.3 | 0.4-2.0 | 0.3-2.3 |
| 80 | 1.22(0.34) | 1.21(0.40) | 1.15(0.42) | 1.09(0.38) |
| | 0.7-1.8 | 0.6-1.8 | 0.5-1.7 | 0.4-1.7 |
| 90 | 1.20(0.36) | 1.22(0.35) | 1.19(0.41) | 1.20(0.40) |
| | 0.7-1.8 | 0.7-1.8 | 0.5-1.8 | 0.5-1.8 |
| All | 1.31(0.47) | 1.23(0.48) | 0.96(0.44) | 0.74(0.51) |
| | 0.2-2.3 | 0.2-2.4 | 0.2-2.6 | 0.1-2.4 |
| | **152 mm d.b.h.** | | | |
| 0 | 1.49(0.68) | 1.30(0.54) | 1.23(0.90) | 1.11(0.85) |
| | 0.8-3.1 | 0.7-2.3 | 0.3-3.2 | 0.1-3.3 |
| 10 | 2.08(0.94) | 1.77(0.75) | 1.05(0.59) | 0.97(0.59) |
| | 0.9-3.5 | 0.8-3.2 | 0.2-2.3 | 0.3-2.0 |
| 20 | 2.28(0.76) | 1.52(0.63) | 1.07(0.66) | 0.94(0.56) |
| | 0.9-3.5 | 0.9-2.8 | 0.5-2.3 | 0.3-2.4 |
| 30 | 2.03(0.73) | 2.00(0.92) | 1.23(0.70) | 1.00(0.71) |
| | 1.3-3.7 | 1.2-4.5 | 0.3-2.3 | 0.3-2.4 |
| 40 | 2.18(0.61) | 1.68(0.66) | 1.33(0.78) | 1.07(0.65) |
| | 1.5-3.9 | 0.6-3.0 | 0.5-2.8 | 0.4-2.7 |
| 50 | 2.33(0.68) | 1.98(0.78) | 1.47(0.81) | 1.28(0.81) |
| | 1.2-3.7 | 0.9-3.3 | 0.3-2.8 | 0.4-2.8 |
| 60 | 2.12(0.76) | 2.04(0.99) | 1.45(0.88) | 1.42(0.94) |
| | 0.7-3.5 | 0.8-4.1 | 0.6-3.7 | 0.3-3.8 |
| 70 | 2.07(1.04) | 2.02(1.16) | 1.72(1.03) | 1.65(0.97) |
| | 0.6-4.8 | 0.7-4.8 | 0.6-3.8 | 0.6-3.6 |
| 80 | 1.86(0.66) | 1.99(0.85) | 1.98(1.14) | 1.80(1.12) |
| | 1.0-3.3 | 0.9-3.3 | 0.5-4.3 | 0.6-4.3 |
| 90 | 1.99(0.89) | 2.05(0.90) | 2.00(0.95) | 1.98(0.96) |
| | 0.8-3.5 | 0.8-3.5 | 0.7-3.5 | 0.8-3.5 |
| All | 2.04(0.79) | 1.83(0.84) | 1.45(0.89) | 1.32(0.88) |
| | 0.6-4.8 | 0.6-4.8 | 0.2-4.3 | 0.1-4.3 |
| | **228 mm d.b.h.** | | | |
| 0 | 2.10(1.20) | 2.25(1.34) | 1.78(0.66) | 1.23(0.71) |
| | 0.4-4.6 | 0.3-5.0 | 0.9-3.2 | 0.5-2.7 |
| 10 | 2.70(1.16) | 2.38(0.93) | 1.39(0.55) | 0.93(0.56) |
| | 1.3-5.0 | 0.8-3.8 | 0.7-2.1 | 0.2-2.0 |
| 20 | 3.09(0.87) | 2.55(1.11) | 1.55(0.71) | 0.94(0.49) |
| | 1.1-4.2 | 1.1-5.0 | 0.5-3.0 | 0.3-1.8 |
| 30 | 2.89(1.00) | 2.63(1.30) | 1.88(0.89) | 0.98(0.63) |
| | 1.7-5.0 | 1.1-5.2 | 1.0-3.5 | 0.1-1.8 |
| 40 | 2.77(1.06) | 2.58(0.93) | 1.83(0.85) | 1.18(0.61) |
| | 1.4-4.5 | 0.8-3.9 | 0.8-3.2 | 0.3-2.3 |
| 50 | 2.78(1.06) | 2.46(1.06) | 1.77(0.81) | 1.40(0.72) |
| | 1.3-5.0 | 1.3-5.0 | 0.8-3.1 | 0.3-2.3 |
| 60 | 2.73(0.79) | 2.55(0.81) | 1.91(0.82) | 1.40(0.77) |
| | 1.3-3.7 | 1.2-3.7 | 0.7-3.1 | 0.3-2.8 |
| 70 | 2.87(0.60) | 2.83(0.87) | 2.13(0.86) | 1.77(0.86) |
| | 1.8-3.8 | 1.8-4.2 | 0.9-3.5 | 0.4-3.0 |
| 80 | 2.39(0.71) | 2.59(0.80) | 2.22(1.00) | 1.92(0.92) |
| | 1.0-3.3 | 1.3-3.7 | 0.8-3.8 | 0.5-3.1 |
| 90 | 2.08(0.75) | 2.11(0.84) | 1.95(0.95) | 2.20(0.97) |
| | 0.9-3.3 | 0.8-3.3 | 0.5-3.4 | 0.5-3.6 |
| All | 2.64(0.96) | 2.49(1.00) | 1.84(0.82) | 1.40(0.82) |
| | 0.4-5.0 | 0.3-5.2 | 0.5-3.8 | 0.1-3.6 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total trees in the sample = 36, that is, 12 of each d.b.h.

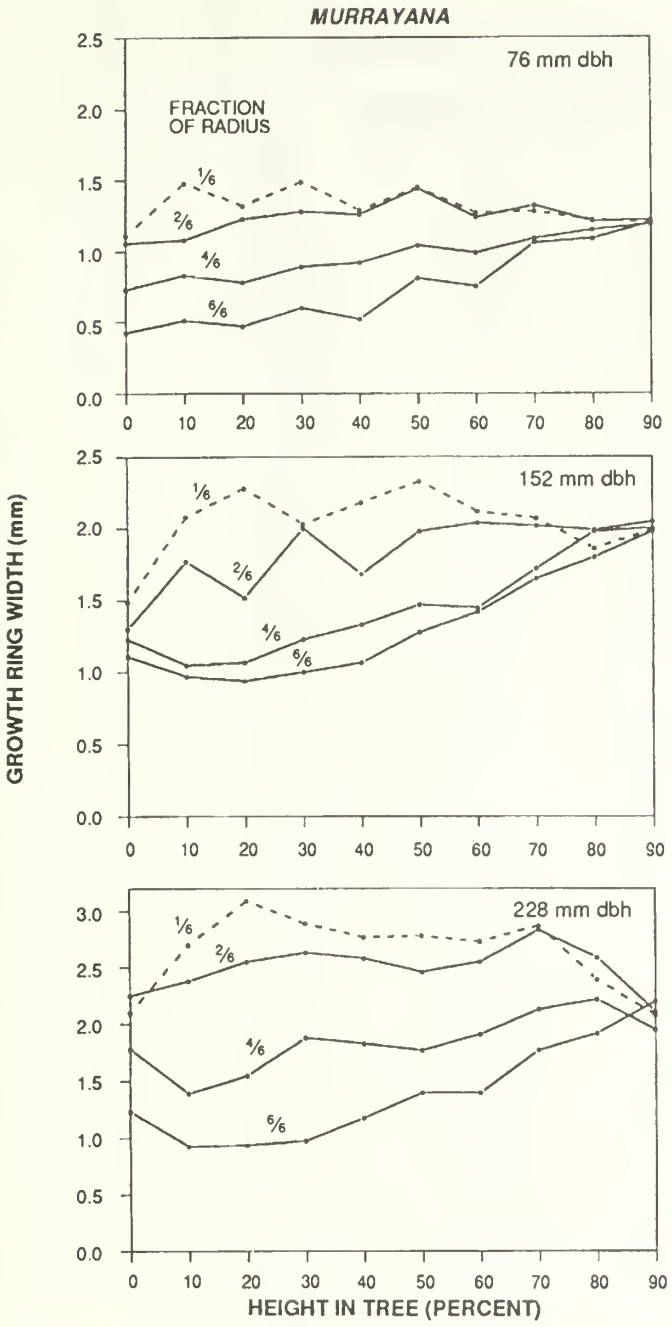



**Figure 28**—Annual growth-ring width in *murrayana* trees of three diameters related to proportions of height in tree and radial distance from pith to bark. Each point on each line is defined by data from 12 trees.

With data from all 36 *murrayana* trees (360 disks) pooled by age in decades, a smooth asymptotic relationship was found in which ring width ($Y$) approached 0.5 mm in the 10th decade and beyond (fig. 27), as follows:

$$Y = 2.1841X^{-0.567}$$

The linearized form of this equation ($\ln Y = \ln a + b \ln X$) has $R^2 = 0.92$, with standard error of the estimate = 0.136 degrees.

## Ring Age Related to Radius and Height at Which Sampled

Age from pith of annual growth rings within the stem is a function of proportion of height in stem and proportion of radius from pith to cambium. At all heights in the trees, the substantial slowing of radial growth with advancing age was evident in both *latifolia* (table 22; fig. 29) and *murrayana* (table 23; fig. 30). In preparing these tabulations, the pith was regarded as year zero.

The data for 20 percent of tree height are typical; that is, years to grow the first 2/6 of the radial distance from pith to cambium averaged only a fraction of the number of years required to grow from 4/6 to 6/6 of the radius, as follows:

| D.b.h. | Pith to 2/6 radius | 2/6 to 4/6 radius | 4/6 to 6/6 radius |
|---|---|---|---|
| *mm* | *Years* | | |
| | *Latifolia* | | |
| 76 | 8.7 | 15.8 | 35.0 |
| 152 | 11.8 | 22.4 | 40.7 |
| 228 | 15.1 | 26.4 | 44.4 |
| | *Murrayana* | | |
| 76 | 9.8 | 12.9 | 23.0 |
| 152 | 10.8 | 21.2 | 29.2 |
| 228 | 11.8 | 18.7 | 34.2 |

At this height, the most stagnated class (76 mm *latifolia*) required 4.0 times the number of years to grow from 4/6 to 6/6 radius than was required to grow from pith to 2/6 radius; the less stagnated *murrayana* trees needed 2.4 to 2.9 times more years to grow from 4/6 to 6/6 radius than from pith to 2/6 radius.

**Table 22**—Age from pith for *latifolia* trees 76 mm, 152 mm, and 228 mm in d.b.h. related to proportion of height from 152-mm-high stump top to apical tip, and to proportion of radial distance from pith to cambium[1]

| Proportion of height | Proportion of radius from pith to cambium | | | |
|---|---|---|---|---|
| | 1/6 | 2/6 | 4/6 | 5/6 |
| *Percent* | ---------- *Years* ---------- | | | |
| | **76 mm d.b.h.** | | | |
| 0 | 6.9 (4.3) | 15.5 (9.7) | 35.5 (18.4) | 73.3 (34.0) |
| | 2-29 | 5-66 | 11-118 | 16-199 |
| 10 | 4.4 (2.3) | 10.5 (5.9) | 29.3 (16.4) | 65.9 (33.2) |
| | 2-13 | 3-38 | 6-104 | 12-192 |
| 20 | 3.7 (1.8) | 8.7 (5.1) | 24.5 (15.4) | 59.5 (31.4) |
| | 1-11 | 3-28 | 5-84 | 10-170 |
| 30 | 3.5 (1.7) | 8.0 (4.5) | 22.3 (13.2) | 53.8 (29.1) |
| | 1-11 | 2-24 | 5-72 | 9-148 |
| 40 | 3.1 (1.6) | 7.0 (3.6) | 19.8 (12.0) | 48.5 (27.8) |
| | 1-9 | 2-17 | 5-57 | 8-138 |
| 50 | 2.9 (1.4) | 6.5 (3.3) | 17.4 (9.9) | 43.6 (25.6) |
| | 1-8 | 2-17 | 4-50 | 7-130 |
| 60 | 2.5 (1.8) | 5.9 (3.9) | 15.9 (9.7) | 38.1 (23.6) |
| | 1-11 | 2-22 | 4-52 | 6-115 |
| 70 | 2.0 (1.1) | 5.2 (3.0) | 13.9 (9.4) | 31.3 (20.0) |
| | 1-6 | 2-14 | 3-60 | 5-107 |
| 80 | 1.6 (0.8) | 3.9 (2.1) | 11.1 (8.2) | 24.2 (17.8) |
| | 1-5 | 1-13 | 3-57 | 4-103 |
| 90 | 1.3 (0.8) | 2.8 (2.0) | 7.3 (6.1) | 14.9 (12.1) |
| | 0-7 | 1-11 | 1-39 | 2-69 |
| | **152 mm d.b.h.** | | | |
| 0 | 10.1 (6.6) | 20.5 (11.9) | 47.5 (23.6) | 91.8 (35.5) |
| | 4-53 | 8-79 | 14-130 | 38-240 |
| 10 | 6.4 (4.3) | 14.0 (8.1) | 39.3 (22.6) | 82.8 (34.9) |
| | 3-29 | 4-49 | 12-151 | 32-232 |
| 20 | 5.2 (2.5) | 11.8 (7.0) | 34.2 (19.2) | 74.8 (31.7) |
| | 2-17 | 4-47 | 10-124 | 28-198 |
| 30 | 4.6 (1.8) | 10.6 (5.4) | 31.7 (17.4) | 68.5 (30.5) |
| | 2-14 | 5-46 | 9-111 | 26-185 |
| 40 | 4.5 (2.6) | 9.9 (5.2) | 27.7 (14.1) | 61.7 (27.5) |
| | 2-18 | 4-35 | 10-84 | 22-148 |
| 50 | 4.3 (2.2) | 9.5 (4.8) | 24.7 (11.5) | 54.6 (25.4) |
| | 2-16 | 4-30 | 10-60 | 19-130 |
| 60 | 4.0 (1.9) | 8.7 (3.9) | 21.9 (10.1) | 47.1 (22.9) |
| | 1-13 | 3-23 | 9-57 | 15-119 |
| 70 | 3.6 (1.6) | 7.9 (3.5) | 19.2 (9.0) | 38.4 (19.4) |
| | 1-8 | 3-21 | 7-48 | 12-102 |
| 80 | 2.9 (1.4) | 6.4 (2.8) | 14.8 (7.3) | 28.9 (16.4) |
| | 1-10 | 2-17 | 4-36 | 8-86 |
| 90 | 1.7 (1.1) | 3.9 (2.1) | 9.4 (5.3) | 17.4 (11.3) |
| | 1-8 | 1-12 | 2-26 | 4-47 |
| | **228 mm d.b.h.** | | | |
| 0 | 13.1 (8.2) | 25.0 (15.0) | 55.4 (28.6) | 104.3 (41.5) |
| | 5-50 | 11-103 | 23-167 | 49-250 |
| 10 | 8.0 (5.8) | 18.1 (12.0) | 47.1 (26.9) | 94.7 (39.1) |
| | 2-48 | 5-79 | 14-160 | 43-216 |
| 20 | 6.8 (5.1) | 15.1 (11.3) | 41.5 (23.9) | 86.9 (37.0) |
| | 2-44 | 5-89 | 16-143 | 32-199 |
| 30 | 6.1 (3.8) | 13.3 (7.6) | 37.9 (20.9) | 79.8 (34.0) |
| | 2-27 | 5-49 | 15-111 | 27-180 |
| 40 | 5.3 (2.4) | 12.1 (6.1) | 32.8 (17.0) | 72.4 (31.0) |
| | 2-15 | 6-39 | 12-83 | 24-160 |
| 50 | 5.5 (2.4) | 12.0 (5.5) | 31.0 (15.8) | 65.0 (28.5) |
| | 2-15 | 5-37 | 12-96 | 20-154 |
| 60 | 5.3 (2.4) | 11.3 (5.5) | 27.2 (13.3) | 56.7 (25.3) |
| | 2-15 | 5-28 | 10-76 | 17-131 |
| 70 | 4.6 (2.2) | 9.8 (4.9) | 23.5 (11.0) | 46.7 (21.2) |
| | 2-13 | 4-30 | 9-58 | 14-105 |
| 80 | 3.6 (1.8) | 8.0 (3.3) | 19.0 (8.5) | 35.4 (15.9) |
| | 1-12 | 3-20 | 6-46 | 9-75 |
| 90 | 2.1 (1.1) | 5.1 (2.6) | 12.3 (6.1) | 21.5 (10.9) |
| | 1-6 | 1-14 | 3-32 | 5-50 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total trees in the sample = 243, that is, 81 of each d.b.h.

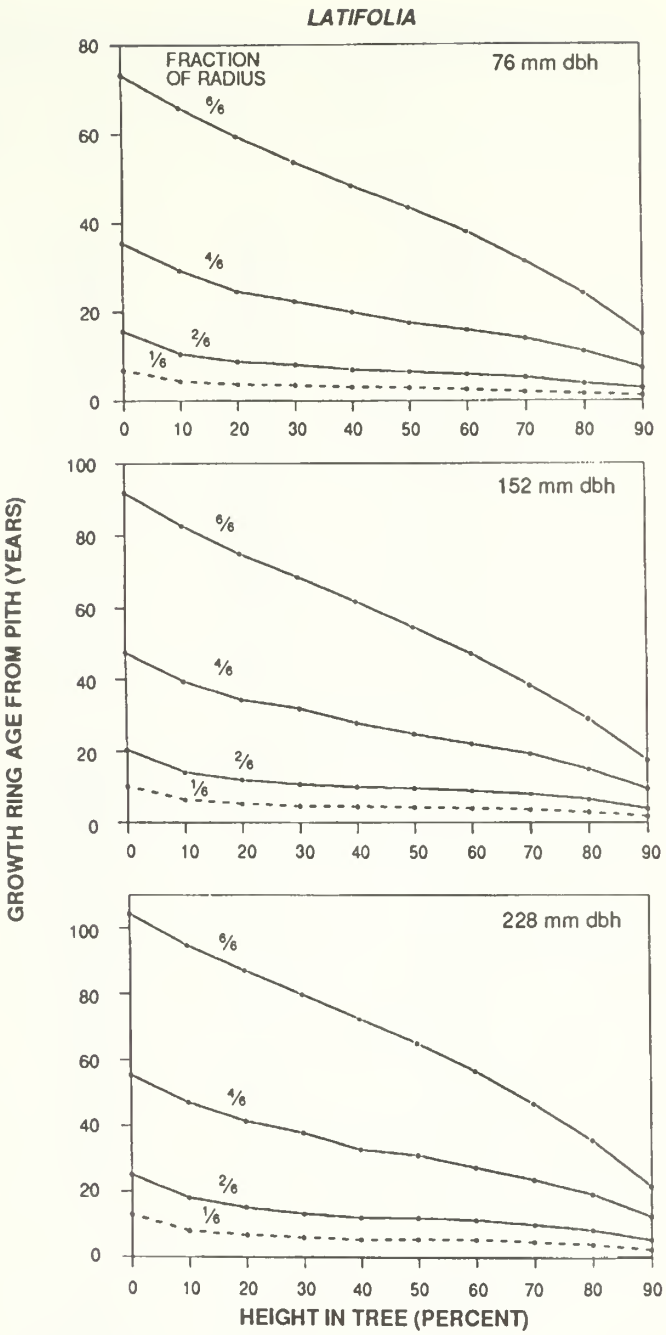



**Figure 29**—Age of annual growth rings at four fractions of disk radius from pith to cambium related to percentage height from 152-mm-high stump top to apical tip in *latifolia* trees 76 mm, 152 mm, and 228 mm in d.b.h. Each point on each line is defined by data from 81 trees.

**Table 23**—Age from pith for *murrayana* trees 76 mm, 152 mm, and 228 mm in d.b.h. related to proportion of height from 152-mm-high stump top to apical tip, and to proportion of radial distance from pith to cambium[1]

| Proportion of height | Proportion of radius from pith to cambium | | | |
|---|---|---|---|---|
| | 1/6 | 2/6 | 4/6 | 6/6 |
| *Percent* | ---------- *Years* ---------- | | | |
| | **76 mm d.b.h.** | | | |
| 0 | 9.8 (7.9) | 17.0 (11.7) | 34.8 (16.2) | 62.5 (23.8) |
| | 3-30 | 5-46 | 14-62 | 29-104 |
| 10 | 5.7 (4.8) | 10.9 (7.9) | 24.9 (10.9) | 53.6 (19.6) |
| | 2-20 | 4-34 | 11-49 | 25-85 |
| 20 | 4.5 (1.7) | 9.8 (4.2) | 22.7 (8.5) | 45.7 (17.2) |
| | 3-8 | 5-18 | 13-36 | 23-78 |
| 30 | 3.3 (1.1) | 7.3 (2.4) | 18.8 (6.3) | 39.3 (16.7) |
| | 1-5 | 4-13 | 11-31 | 20-75 |
| 40 | 3.3 (1.8) | 7.0 (3.3) | 16.6 (9.1) | 33.3 (16.8) |
| | 2-7 | 4-14 | 9-38 | 17-73 |
| 50 | 2.8 (1.0) | 5.8 (2.0) | 13.4 (7.4) | 28.0 (15.5) |
| | 2-5 | 4-9 | 8-34 | 14-68 |
| 60 | 2.7 (2.1) | 6.4 (5.6) | 13.3 (9.5) | 23.8 (14.7) |
| | 1-8 | 3-23 | 6-41 | 11-63 |
| 70 | 2.0 (0.9) | 4.5 (2.0) | 9.8 (4.8) | 17.0 (9.1) |
| | 1-4 | 3-10 | 5-21 | 8-38 |
| 80 | 1.5 (0.7) | 3.2 (1.3) | 6.9 (3.5) | 11.4 (6.0) |
| | 1-3 | 2-6 | 4-14 | 6-24 |
| 90 | 1.0 (0.0) | 1.9 (0.8) | 3.8 (1.8) | 6.0 (2.9) |
| | 1-1 | 1-3 | 2-8 | 3-12 |
| | **152 mm d.b.h.** | | | |
| 0 | 9.9 (4.8) | 20.6 (8.4) | 45.8 (20.4) | 81.8 (35.1) |
| | 4-18 | 9-33 | 24-86 | 41-149 |
| 10 | 6.2 (2.0) | 13.1 (4.5) | 36.7 (13.5) | 70.3 (30.3) |
| | 2-9 | 5-19 | 14-61 | 35-133 |
| 20 | 4.9 (1.9) | 10.8 (3.8) | 32.0 (13.0) | 61.2 (27.4) |
| | 3-8 | 6-18 | 15-61 | 29-115 |
| 30 | 5.0 (1.5) | 10.3 (2.7) | 26.5 (10.8) | 53.7 (26.1) |
| | 3-7 | 6-15 | 14-51 | 24-105 |
| 40 | 4.2 (1.8) | 8.9 (3.6) | 24.0 (12.4) | 46.3 (24.7) |
| | 2-8 | 5-18 | 11-55 | 17-94 |
| 50 | 4.0 (1.2) | 8.3 (3.3) | 20.0 (9.2) | 39.8 (22.8) |
| | 2-7 | 5-17 | 9-40 | 14-85 |
| 60 | 3.5 (1.5) | 7.7 (4.6) | 18.3 (10.6) | 33.3 (20.3) |
| | 2-6 | 3-16 | 7-41 | 10-74 |
| 70 | 3.2 (1.8) | 6.7 (4.3) | 15.3 (9.3) | 25.7 (16.3) |
| | 1-7 | 2-17 | 4-36 | 7-59 |
| 80 | 2.9 (1.5) | 5.3 (2.5) | 10.6 (6.0) | 17.3 (10.6) |
| | 1-7 | 2-11 | 4-21 | 6-34 |
| 90 | 1.3 (0.7) | 2.7 (1.9) | 6.0 (4.3) | 9.7 (7.3) |
| | 1-3 | 1-7 | 2-15 | 3-24 |
| | **228 mm d.b.h.** | | | |
| 0 | 12.9 (4.8) | 25.5 (14.1) | 50.3 (25.7) | 85.5 (32.8) |
| | 5-22 | 9-63 | 22-111 | 45-143 |
| 10 | 6.8 (2.6) | 14.0 (6.1) | 37.0 (17.5) | 73.8 (29.0) |
| | 3-12 | 7-29 | 18-76 | 40-119 |
| 20 | 5.6 (1.3) | 11.8 (3.9) | 30.5 (12.8) | 64.7 (25.6) |
| | 4-8 | 7-19 | 17-57 | 37-106 |
| 30 | 5.3 (1.6) | 11.5 (3.9) | 27.3 (11.8) | 57.5 (22.8) |
| | 3-8 | 5-21 | 10-56 | 32-95 |
| 40 | 5.3 (1.9) | 11.3 (3.8) | 26.2 (10.3) | 50.3 (21.8) |
| | 3-8 | 6-17 | 13-47 | 25-87 |
| 50 | 4.6 (1.4) | 9.4 (3.2) | 21.7 (8.2) | 43.0 (19.2) |
| | 3-8 | 5-15 | 13-40 | 22-76 |
| 60 | 4.3 (1.7) | 8.3 (3.3) | 18.8 (8.0) | 35.6 (16.9) |
| | 2-7 | 5-16 | 11-35 | 17-67 |
| 70 | 3.4 (1.2) | 6.6 (2.7) | 14.7 (5.9) | 28.0 (14.4) |
| | 2-6 | 4-12 | 8-26 | 13-57 |
| 80 | 2.8 (1.2) | 5.7 (2.4) | 11.6 (6.0) | 20.9 (12.8) |
| | 1-5 | 3-10 | 6-25 | 9-48 |
| 90 | 1.5 (0.8) | 3.1 (1.7) | 7.0 (4.5) | 11.7 (7.7) |
| | 1-3 | 1-6 | 3-17 | 5-26 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values. Total trees in the sample = 36, that is, 12 of each d.b.h.

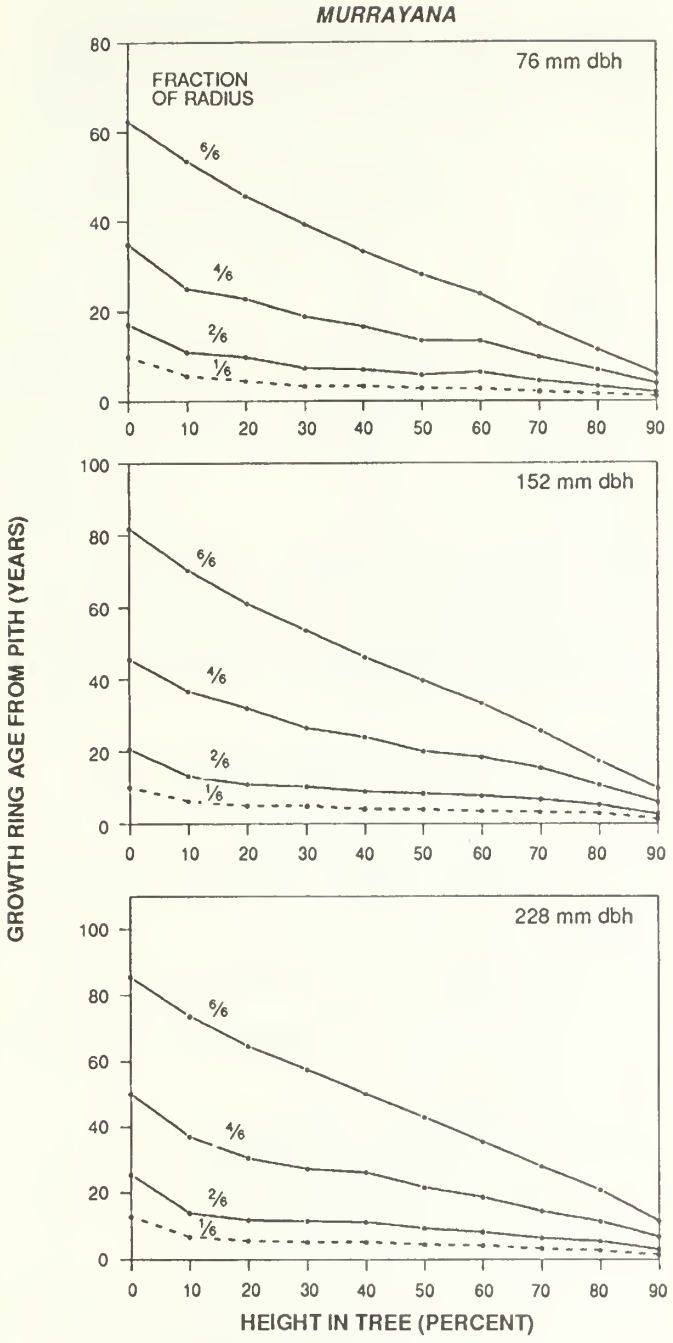



**Figure 30**—Age of annual growth rings at four fractions of disk radius from pith to cambium related to percentage height from 152-mm-high stump top to apical tip in *murrayana* trees 76 mm, 152 mm, and 228 mm in d.b.h. Each point on each line is defined by data from 12 trees.

## Tree Height Growth

Height from 152-mm-high stump top to apical tip of all trees sampled averaged greater for *latifolia* than for *murrayana* (table 1) as follows:

| D.b.h. | *Latifolia* | *Murrayana* |
|---|---|---|
| *mm* | *Meters* | |
| 76 | 9.3 | 7.4 |
| 152 | 15.6 | 13.7 |
| 228 | 19.1 | 18.7 |

The years required for the trees to reach a particular proportion of tree height varied greatly (table 24); for example, time for *latifolia* trees to reach 60 percent of their height had averages and ranges as follows:

| D.b.h. | Average | Range |
|---|---|---|
| *mm* | *Years* | |
| 76 | 35.2 | 10-84 |
| 152 | 44.7 | 20-156 |
| 228 | 47.7 | 21-140 |

| D.b.h. | 60 percent of tree height | |
|---|---|---|
| *mm* | *Meters* | *Feet* |
| 76 | 5.58 | 18.3 |
| 152 | 9.36 | 30.7 |
| 228 | 11.46 | 37.6 |

Annual height growth averaged linear up to about 60 percent of height at sample age; from 60 to 100 percent of height the relationship is curvilinear—reflecting a slowing of height growth (fig. 31). Thus at the time these trees had reached 60 percent of the height at which sampled, they had averaged 15.9 cm/year height growth for trees 76 mm d.b.h., 20.9 cm/year for trees 152 mm d.b.h., and 24.0 cm/year for trees 228 mm d.b.h. By the age at which the trees were sampled (100 percent of height), their average annual height growth had slowed. That is, over the entire age of the trees average annual height growth was only 12.7 cm/year for trees 76 mm d.b.h., 17.0 cm/year for trees 152 mm d.b.h., and 18.3 cm/year for trees 228 mm d.b.h.

**Table 24**—Years required for *latifolia* and *murrayana* trees 76 mm, 152 mm, and 228 mm in d.b.h. to reach various proportions of total tree height from 152-mm-high stump top to apical tip[1]

| Proportion of height | Tree d.b.h. | | |
|---|---|---|---|
| | 76 mm | 152 mm | 228 mm |
| *Percent* | - - - - - - - - - - - - *Years* - - - - - - - - - - - - | | |
| | ***Latifolia* (81 trees/d.b.h.)** | | |
| 10 | 7.3(4.28) | 9.1(4.42) | 9.6(5.99) |
| | 1-24 | 2-24 | 1-45 |
| 20 | 13.7(7.63) | 17.0(8.94) | 17.4(8.27) |
| | 3-48 | 6-64 | 4-51 |
| 30 | 19.5(9.50) | 23.4(11.51) | 24.5(12.05) |
| | 5-54 | 9-82 | 9-79 |
| 40 | 24.8(11.35) | 30.1(14.40) | 31.9(16.51) |
| | 8-63 | 13-93 | 14-111 |
| 50 | 29.7(13.61) | 37.2(17.53) | 39.3(19.28) |
| | 9-69 | 16-124 | 17-126 |
| 60 | 35.2(16.23) | 44.7(20.24) | 47.7(22.24) |
| | 10-84 | 20-156 | 21-140 |
| 70 | 41.9(20.60) | 53.5(22.92) | 57.6(25.65) |
| | 11-129 | 24-174 | 25-160 |
| 80 | 49.1(23.65) | 62.9(25.95) | 68.9(30.56) |
| | 12-144 | 29-201 | 29-181 |
| 90 | 58.4(27.45) | 74.4(29.29) | 82.8(35.09) |
| | 13-169 | 34-223 | 38-212 |
| 100 | 73.3(33.95) | 91.8(35.45) | 104.3(41.51) |
| | 16-199 | 38-240 | 49-250 |
| | **Murrayana (12 trees/d.b.h.)** | | |
| 10 | 8.9(6.08) | 11.6(5.65) | 11.7(5.14) |
| | 2-20 | 5-21 | 5-24 |
| 20 | 16.8(10.11) | 20.7(8.29) | 20.8(8.30) |
| | 4-37 | 9-34 | 8-37 |
| 30 | 23.2(12.66) | 28.2(10.30) | 28.0(10.91) |
| | 9-51 | 13-44 | 13-48 |
| 40 | 29.2(13.80) | 35.5(12.40) | 35.2(12.50) |
| | 12-58 | 17-55 | 17-61 |
| 50 | 34.5(15.34) | 42.1(14.01) | 42.5(14.96) |
| | 15-64 | 23-64 | 21-73 |
| 60 | 38.8(16.23) | 48.5(16.42) | 49.9(17.86) |
| | 18-67 | 26-75 | 24-87 |
| 70 | 45.5(17.36) | 56.2(20.55) | 57.5(21.11) |
| | 20-74 | 30-90 | 30-104 |
| 80 | 51.1(19.22) | 64.6(26.27) | 64.6(24.04) |
| | 23-83 | 34-117 | 35-120 |
| 90 | 56.5(21.93) | 72.2(29.50) | 73.8(27.74) |
| | 25-94 | 37-131 | 39-131 |
| 100 | 62.5(23.84) | 81.8(35.10) | 85.5(32.76) |
| | 29-104 | 41-149 | 45-143 |

[1]Entries in the body of the table show the mean, followed by the standard deviation in parentheses; listed below these statistics is the range of values.

A similar computation (from table 24) for *murrayana* suggests that *murrayana* annual height growth was more nearly linear throughout tree age to date sampled (fig. 31), as follows:

| D.b.h. | To 60 percent of tree height | |
|---|---|---|
| | ***Latifolia*** | ***Murrayana*** |
| *mm* | *cm annual height growth* | |
| 76 | 15.9 | 11.5 |
| 152 | 20.9 | 16.9 |
| 228 | 24.0 | 22.5 |

| D.b.h. | To 100 percent of tree height | |
|---|---|---|
| | ***Latifolia*** | ***Murrayana*** |
| *mm* | *cm annual height growth* | |
| 76 | 12.7 | 11.8 |
| 152 | 17.0 | 16.7 |
| 228 | 18.3 | 21.9 |

Thus *latifolia* trees had greater annual height growth than *murrayana* for the first 60 percent of tree height, but at 100 percent of tree height the average annual height increments were more nearly equal for the two varieties.

## Estimate of Tree Height Based on Stump Diameter and Age

It is sometimes useful to estimate tree height from parameters measurable at 152-mm-high stump top, as follows:

$H$ = tree height from 152-mm-high stump top to apical tip, meters

$D$ = diameter (by diameter tape) inside bark, millimeters

$A$ = age at stump top, years

$W$ = average width of annual growth rings at stump top, millimeters = $(D/2)/A$

***Latifolia***—Regression equations based on data from 243 trees:

$$H = 5.457 + 0.056D$$

$r = 0.8317$; $R^2 = 0.692$

Standard error of estimate = 2.66 m

Addition of average growth-ring width ($W$) and age at stump top ($A$) contributed only a little to the prediction equation, as follows:

$$H = 7.586 + 0.068D - 2.19W - 0.0222A$$

$R^2 = 0.703$

Standard error of the estimate = 2.63 m

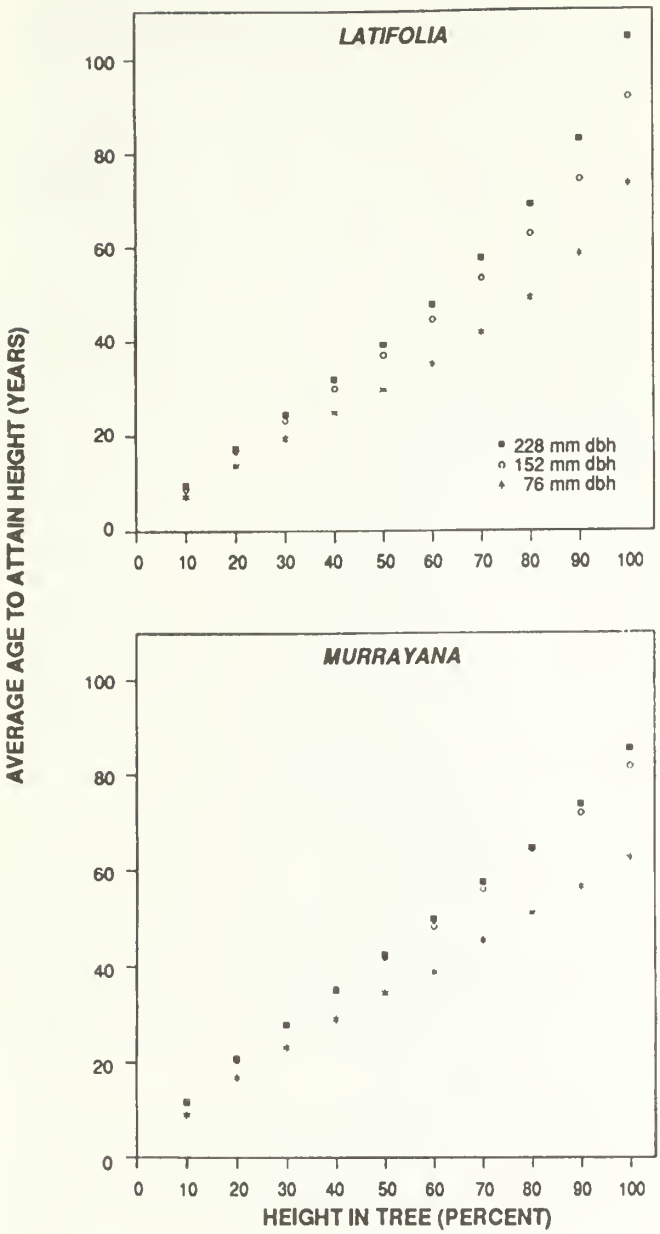



**Figure 31**—Average number of years to attain various proportions of tree height from 152-mm-high stump top to apical tip. Data are based on 81 or 12 trees of each d.b.h. for *latifolia* and *murrayana*, respectively.

***Murrayana***—Regression equations based on data from 36 trees:

$H = 2.799 + 0.064D$

$r = 0.8045$; $R^2 = 0.647$

Standard error of estimate = 3.51 m

Addition of average growth-ring width ($W$) significantly improved the prediction equation, as follows:

$H = 3.681 + 0.081D - 3.167W$

$R^2 = 0.714$

Standard error of the estimate = 3.21 m

## SUMMARY—AMONG-TREE VARIATIONS

When evaluating entire stems of *latifolia* trees, greatest tree-average volume-weighted maximum spirality was found in old, large-diameter, heavy trees with heavy stump-root systems, much heartwood and eccentric piths in stems, many cones, and long, wide crowns comprised of many thick-barked, large-diameter branches bearing much foliage. Spirality tended to be greater in extreme north and south latitudes than at midlatitudes of the species range. Tree-average spirality did not vary significantly with elevational zone. Among the 243 *latifolia* trees examined, variation was substantial. Volume-weighted, tree-average maximum spiral grain ranged from 1.5 to 10.7 degrees and averaged 3.61 degrees for trees 76 mm d.b.h., 4.14 degrees for trees 152 mm d.b.h., and 4.79 degrees for trees 228 mm d.b.h.

Variety *murrayana* did not vary significantly from *latifolia* in tree-average volume-weighted maximum spirality.

When evaluating entire stems of *latifolia* trees, greatest percentage of right-hand spirality at point of maximum spiral grain in 10 sections sampled in each stem was found in slow-growing old trees with large live branches, dense stem bark, thick stump bark, and with heavy stems having eccentric piths and large heartwood diameter at stump height. Wood and bark of such trees tend to be low in percentage moisture content. Also, percentage of right-handedness tended to be greater (35.2 percent) at the northernmost latitude of *latifolia* sampled—60 degrees, than in the southernmost latitudes of 40 and 42.5 degrees (average of 17.3 percent). In the 243 *latifolia* trees examined, variation was extreme; that is, percentage of right-handedness in maximum values of spiral grain ranged from 0 to 100 percent. Tree-average percentage of right-handedness of maximum spirality did not vary significantly between entire populations sampled from the two varieties; the average for *murrayana* was 26.7 percent, that for *latifolia* 26.0 percent.

Maximum spirality most frequently occurred at stump height in both varieties, with a second and lesser concentration of maximum spirality occurring at 70 percent of tree height in *latifolia* and 80 percent in *murrayana*. The maximum spirality at stump height tends to be right-hand and near the bark, particularly in large trees, whereas maximum spirality in upper stem sections tends to be left-hand.

With data for all trees pooled by variety, patterns 1, 1A, and 3 (figs. 8 and 11) predominated, accounting for 78.4 percent of the tree-average patterns in *latifolia* and 82.2 percent in *murrayana*. Virtually all trees had some degree of spirality. With data

from all 243 *latifolia* trees pooled, 17.1 percent of the disks in each tree displayed pattern 1 (left-hand with increasing left-hand spirality away from pith). Prevalence of pattern 1 was significantly greater in trees 76 mm in d.b.h. than in those 152 mm or 228 mm in d.b.h., and pattern 1 was significantly more prevalent in low elevational zones than in medium or high zones. Also prevalence of pattern 1 was generally greater in southern latitudes than in northern.

Both patterns 1 and 1A show only left-hand spiral grain, but in pattern 1A the degree of spirality reaches a maximum away from the pith and then decreases toward the bark. With data from all 243 *latifolia* trees pooled, 25.9 percent of the disks in each tree displayed pattern 1A. Small-diameter trees, and those in medium or upper elevational zones, tended to have a larger percentage of pattern 1A disks than large-diameter trees and those in low elevational zones. The percentage of pattern 1A was lowest in the most southerly latitude and in the most northerly latitude.

Pattern 3 (left-hand spirality near the pith changing to right-hand spirality with increased age from pith) was most frequent. With data from all 243 *latifolia* trees pooled, 35.4 percent of the disks in each tree displayed pattern 3; this percentage did not vary significantly with d.b.h. class.

When entire varietal populations sampled were compared, there were no significant differences in average percentages of the three dominant patterns.

In the *latifolia* trees sampled, volume-weighted tree-average growth ring width averaged 1.11 mm with standard deviation of 0.6 mm and range from 0.2 to 3.2 mm—the variability reflecting the prevalence of trees that stagnate at an early age in natural unthinned stands. Average growth ring width in these trees varied significantly with each of the three major factors in the study—d.b.h., elevational zone, and latitude. Average growth ring width was positively correlated with d.b.h., that is, ring widths averaged 0.81 mm in trees 76 mm d.b.h., 1.12 mm width in trees 152 mm d.b.h., and 1.40 mm width in trees 228 mm d.b.h. While not significantly correlated with absolute elevation, growth ring width had significant negative correlation with elevational zone; that is, ring width averaged 1.34 mm in low elevational zones, 1.05 mm in medium elevational zones, and 0.94 mm in high elevational zones. Growth ring width in *latifolia* averaged widest (1.37 mm) at latitudes 42.5, 45, and 47.5 degrees; rings were narrowest (0.69 mm) in trees from the northernmost latitude sampled (60 degrees). Stems with a high percentage of left-hand spirality have wider growth rings than those with predominantly right-hand maximum spirals.

In entire populations sampled, volume-weighted tree-average annual growth ring width was significantly greater in *murrayana* (1.40 mm) than in *latifolia* (1.11 mm). As with *latifolia*, means were positively correlated with d.b.h.

Tree ages at 152-mm-high stump top averaged greater for *latifolia* than for *murrayana* of equal d.b.h., and *latifolia* trees averaged taller from stump top to apical tip. As a result of this height differential, *latifolia* trees of each d.b.h. class had more stemwood volume and weight ovendry than those of *murrayana*—but took more years to achieve this volume and weight. Volume and weight growth per year was not greatly different, therefore, for the two varieties; with all data from both varieties pooled, stemwood volume growth was 275, 1,440, and 3,770 $cm^3$ per year for trees 76 mm, 152 mm, and 228 mm in d.b.h. Annual increment of ovendry stemwood weight growth averaged 0.13, 0.62, and 1.54 kg per year for trees 76 mm, 152 mm, and 228 mm in d.b.h. These data reflect the typical early stagnation of suppressed small trees in unthinned natural stands.

In *latifolia* annual height growth averaged linear up to about 60 percent of tree height, but thereafter slowed. By the time these trees reached 60 percent of the height at which sampled, they had averaged 15.9 centimeters per year height growth in trees 76 mm d.b.h., 20.9 centimeters in trees 152 mm d.b.h., and 24.0 centimeters in trees 228 mm d.b.h. By the age at which the trees were sampled (100 percent of height), their average height growth had slowed; that is, over the entire age of the trees average annual height growth was only 12.7 centimeters per year for trees 76 mm d.b.h., 17.0 centimeters for trees 152 mm d.b.h., and 18.3 centimeters for trees 228 mm d.b.h. (fig. 31).

*Murrayana* height growth was more nearly linear to age at which sampled, and averaged 11.8, 16.7, and 21.9 centimeters per year throughout tree age to date of sample in trees 76 mm, 152 mm, and 228 mm in d.b.h. (fig. 31).

## SUMMARY—WITHIN-TREE VARIATIONS

In trees of both varieties and all diameters spirality patterns 1, 1A, and 3 predominate. The proportions of these three major patterns differ significantly with height in tree for each diameter class. Prevalence of pattern 1 is low in lower stem sections, but increases rapidly in upper sections. Incidence of pattern 1A is least in the lower stem, increases to a maximum near 70 percent of tree height, and then decreases somewhat in uppermost stem sections. Prevalence of pattern 3 increases from an initially high proportion (30 to 40 percent) at stump height to a maximum near 10 or 20 percent of tree height and then decreases sharply in the upper stem.

As noted previously, maximum spirality most frequently occurred at 152-mm-high stump top in both varieties, with a second and lesser concentration of maximum spirality occurring at 70 percent of tree height for *latifolia* and 80 percent for *murrayana*. Average angularity of maximum spirality observed at each percentage of tree height differed somewhat between varieties. *Murrayana* spirality was inversely correlated with height—particularly in trees 76 mm and 152 mm in d.b.h.; *latifolia* maximum spirality at 10 percent of tree height and above did not vary much with increasing height in tree. In *latifolia* trees at stump height, maximum spirality occurred most frequently in rings more than 80 years and 80 mm from the pith. With increasing height in stems, the point of maximum spirality occurred increasingly closer to the pith. For example, at 60 percent of tree height one-half to three-fourths of the maximums occurred within the first 20 years and first 20 mm of distance from pith. *Murrayana* displayed similar radial distribution patterns of maximum spirality.

In both *latifolia* and *murrayana* the greatest percentage of right-hand spirality is found in lower stem sections in outermost stem layers; least percentage of right-hand spirality is found near the pith. The data suggest that sawlogs from lower stem sections of both varieties will display about equal percentages of right-hand and left-hand spirality at log surface—but virtually all will have left-hand spirality adjacent to the pith. The maximum degree of spirality observed in each section (at whatever radius this maximum occurred) tended toward right-handedness in lower stem sections and was predominantly left-hand in upper stem sections.

At stump height slightly less than half of the sections had same-direction spirality at the cambium on opposing disk radii. This percentage increased with increasing height in the trees. From 30 through 60 percent of tree height, slightly less than two-thirds of the sections had same-direction spirality at the cambium on opposing disk radii; and at 90 percent of tree height, nearly 90 percent had same direction spirality. When sampled on short and long opposed radii (piths are eccentric to some degree in all sections) no significant differences were discernible in spirality direction just inside the cambium. There is a weak tendency for greatest degree of spirality to occur on the long, rather than the short, disk radius.

Degree of spirality in both *latifolia* and *murrayana* was poorly correlated with the width of the annual ring in which spirality was measured. Both degree and direction of spirality were, however, correlated with annual ring age from pith—the relationship differing with each of the three major spirality patterns (1, 1A, or 3).

When data from all 243 *latifolia* trees (2,430 disks) and all 36 *murrayana* trees (360 disks) were pooled by variety, and data averaged by age-class from pith in decades, a strong negative linear relationship between ring age from pith and spiral grain was observed (fig. 23). In both varieties, spirality changed linearly from 2+ degrees of left-hand spirality in proximity of the pith to about 2 degrees of right-hand spirality at ring ages greater than 10 decades.

Greatest maximum disk spirality—sign ignored—may be found in thick-barked, out-of-round sections of low moisture content but high heartwood content, and with eccentric piths. Additionally, greatest maximum spirality may be found in sections comprised of long earlywood fibers and of fibers characterized by large tangential diameters.

All heights and tree diameters considered, annual growth rings averaged wider in *murrayana* than in *latifolia*. In both varieties disk-average growth ring width was positively correlated with both tree d.b.h. and height in tree. At every height in trees of both varieties and all diameters, annual growth-ring width was greatest near the pith and diminished near the bark. It is worth noting and emphasizing that at ⅚ radius, growth-ring widths in *latifolia* trees of all three diameters averaged significantly less than 1 mm except in uppermost sections of the larger trees.

At all heights in both *latifolia* and *murrayana* trees, the substantial slowing of radial growth was evident. The data for 20 percent of tree height are typical. At this height, the most stagnated class (76 mm *latifolia*) required 4.0 times the number of years to grow from ⅙ to ⅚ radius than was required to grow from pith to ⅔ radius; the less stagnated *murrayana* trees needed 2.4 to 2.9 times more years to grow from ⅙ to ⅚ radius than from pith to ⅔ radius.

Considering all stem sections examined, annual ring width diminished from about 2 mm near the pith to asymptotically approach 0.3 mm in *latifolia* and 0.5 mm in *murrayana* in outermost layers of trees 10 or more decades in age (fig. 27).

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Wood samples representing entire trees were collected from lodgepole pine varieties *latifolia* and *murrayana* 76 mm, 152 mm, and 228 mm d.b.h., growing at low, medium, and high elevations, and in latitudes from 37.5 to 60 degrees, in western North America. Spiral grain averaged 3.61, 4.14, and 4.79 degrees in *latifolia* of the three diameters; *murrayana* was not significantly different. Spirality was greatest near stump top and was linearly related to age from pith, changing from about 2 degrees left hand adjacent to pith to about 2 degrees right hand by the 11th (*murrayana*) to 14th (*latifolia*) decade. Annual ring width diminished from about 2 mm near the pith to 0.3 in *latifolia* and 0.5 in *murrayana* in outer stemwood 10 or more decades old.

KEYWORDS: slope of grain, annual ring width, growth rate, growth rings, height growth, pith eccentricity, stem form, geographic variation, growth and yield, *Pinus contorta* var. *latifolia* Engelm., *Pinus contorta* var. *murrayana* (Grev. and Balf.) Engelm., spiral grain

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